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An Assessment of Correlations Between Laboratory and Full Scale Experiments for the FAA Aircraft Fire Safety Program, Part 3: ASTM E 84

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Washington, DC 20234

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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NOMENCLATURE

A_o Area of specimen covered by the exposure flame (m^2)

A_f Area of specimen covered by flame during test (m^2)

A_p Area of specimen being pyrolyzed (m^2)

A_T Area under flame spread distance versus time curve in the E84 tunnel ($m \cdot s$)

C Heat capacity ($kJ/kg \cdot K$)

d Distance of flame spread (m)

d_{MAX} Distance of maximum flame spread (m)

d_o Distance to end of exposure flame (m)

$\dot{d}$ Maximum flame spread rate (m/s)

f Ratio of flame area to total rate of heat release by flame (m^2/kW)

K Thermal conductivity ($kW/m \cdot K$)

$\bar{q}$ Average rate of heat release per unit area of the pyrolysing surface (kW/m^2)

$\dot{q}''_f$ Heat transfer from flame to surface (kW/m^2)

$\dot{Q}$ Total rate of heat release (kW)

$\dot{Q}'$ Total rate of heat release per unit width

t Time (s)

t' Time for flame to reach its maximum distance (s)

t* Time for flame to reach the end of the tunnel (s)

t_T Time of test (s)

T_p Temperature of pyrolyzing surface (K)

T_s Temperature of surface ahead of the flame (K)

$\dot{V}_p$ Areal rate of flame spread (m^2/s)

W Width of tunnel (m)

X_o Distance to end of burner flame (m)

X_f Distance to end of flame in tunnel (m)

ρ Density (kg/m^3)

τ_p Time required to heat material ahead of flame to the pyrolysis temperature (s)

ABBREVIATIONS

ACB	Asbestos Cement Board
AMB	Asbestos Mill Board
ASTM	American Society for Testing and Materials
CFM	Cubic feet per minute
F.R.	Flame Retardant treated
FSC*	Flame Spread Classification
FSI	Flame Spread Index
GWL	Present method of calculating FSC derived by George Williams-Leir
NBS	National Bureau of Standards
NRCC	National Research Council of Canada
U.L.	Underwriters Laboratories

* FSC and FSI are used interchangably in this report. The flame spread results in the tunnel were expressed as the FSC when much of the data covered in this report was taken.

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ABSTRACT

A comparison is presented between the room fire performance in four different full-scale fire test series and the flame spread classification obtained by the ASTM E 84 tunnel test for a wide range of materials. A good correlation is obtained only for conventional interior finish materials. A flame spread hypothesis is presented to account for the stopping of the flame in the tunnel and the difference in the fire performance of materials in the tunnel test and in the room fire test.

Key Words: ASTM E 84; fire tests; flame spread; heat release; room fire.

1. INTRODUCTION

The complete characterization of a room fire includes the temporal and spatial distribution of the temperature, gas velocity, gas and smoke concentrations, heat flux, etc. It also includes the boundary and initial conditions, such as the dimensions of the room (including the location and size of the openings), the surface covered by the test material, the materials covering the remainder of the room, the characteristics of the ignition source, and the temperature and gas concentration of the incoming air. The ranking of materials is dependent to some extent on these boundary and initial conditions, as well as upon the particular criteria used to evaluate the severity of the room fire. The correlation of the flame spread index determined by the ASTM E 84 tunnel test [1][1] with full-scale room fires is hampered by the fact that there is no unique ranking of materials with respect to their hazard in a room fire. The ranking will depend on the parameter selected for comparison. Some parameters which have been used for this purpose are (1) the maximum gas temperature averaged over a set of measurements obtained above some height in the room; (2) the maximum gas temperature at a single point near the center of the ceiling or the top of the doorway; (3) the maximum heat flux at the center of the floor; (4) the time to flashover, variously defined by the attainment of some upper gas temperature, usually 600°C (at a single thermocouple or averaged over a set of thermocouples) by a radiant flux of 20 kW/m^2 at the center of the floor, by the ignition of a combustible material indicator located in the lower part of the room, or in some cases, by a rapid increase in the burning rate of the fire; (5) time to flameover, defined as the first appearance of flame extending beyond the doorway; and, (6) the maximum concentration of smoke or toxic gases, or the times at which they exceed some specified threshold values.

Generally, we are concerned whether a material will lead to room flashover and, if so, how long will it take. Since most combustible materials will lead to flashover if the ignition conditions are severe enough, we would like to know just how severe these ignition conditions must be (Is a burning wastebasket sufficient? A burning overstuffed chair?). This necessitates running a series of tests with ignition conditions of varying severity. Such tests are usually prohibitively expensive. Therefore, we simply resort to testing all of the materials at a fixed condition and ranking their performance. Since material performance rankings will be somewhat dependent on the conditions, there may be a tendency to pick conditions which could move one material up or down in relative ranking. Therefore, a room fire test is being proposed in ASTM in

[1] Numbers in brackets refer to the literature references listed at the end of this report.

which the conditions are standardized. The impact of some of the variables in the room fire test is discussed in ASTM E 603 [2].

The ASTM E 84 tunnel test measures the flame spread of the specimen material relative to that of asbestos cement board (ACB) and red oak flooring under similar test conditions. A 0.51-m (20-in) wide and 7.3-m (24-ft) long specimen forms the last 7.3 m (24 ft) of the ceiling of a 7.6-m (25-ft) long tunnel, which is 0.46 m (1.5 ft) wide and 0.31 m (1 ft) deep. The first 0.31 m (1 ft) of the ceiling at the fire end of the tunnel is ACB. There are two gas burners, located 0.31 m (1 ft) from this end, which produce a diffusion flame that extends 1.6 m (4.5 ft) along the tunnel. Air is supplied at a rate of 170 L/s (360 CFM) through a 76-mm (3-in) high opening at the fire end. One side of the tunnel is equipped with viewing windows through which the distance between the flame front and the burner flame can be continuously monitored during the 10-minute test. The length of the burner flame, i.e., 1.6 m (4.5 ft), is subtracted to get the flame spread distance for the specimen. In plotting the flame spread distance versus time, any recession of the flame front is ignored so that the curve monotonically increases (or becomes flat). The area, A_T, under this adjusted curve, is then used to calculate the flame spread index (FSI).

If $A_T \leq 1780$ m • s (97.5 ft • min), then FSI = $0.0281\ A_T\ (0.515\ A_T)$.

If $A_T > 1780$ m • s (97.5 ft • min), then FSI = $\dfrac{89700}{3560-A_T}\quad\dfrac{4900}{195-A_T}$.

This calculational procedure is known as the GWL method. Note that the FSI, formerly called FSC, does not indicate the flame spread rate. If the flame spread distance to the end of the tunnel, 5.95 m (19.5 ft), is achieved in 10 minutes due to a rather slow linear progression from zero time, the FSI would be 50. If the flame were to spread half of that distance in a few seconds (indicating a very great rate of flame spread) and then stops, the FSI would also be 50.

Prior to 1976, the flame spread classification (FSC) was based on the time required for the flame to travel to the end of the tunnel, unless it stopped within the tunnel. In the latter case, it was based strictly on the maximum distance reached. The present calculational method was introduced to eliminate an important discontinuity. A material which spread flame just to the end of the tunnel in a very short time would have a very high rating for specimens for which the flame just passed over the end, but very low ratings for those specimens for which the flame stopped just short of the end. Otherwise, the new method was designed to produce ratings similar to those obtained by the old method.

Because of the low ratings achieved by some foam plastics in the tunnel, in contrast to their rapid fire buildup in a room, the National Research Council of Canada (NRCC) developed the formula

$$FSC = 5550\, d_{MAX}/t',$$

where d_{MAX} is the maximum flame spread distance in meters and t' is the time required to reach it in seconds.

This report presents a comparison of the ASTM E 84 tunnel test results with those of the full-scale room fire tests involving the same materials. Data from the ASTM E 162 [3], the NBS heat release rate calorimeter [4], the ease of ignition test being developed at NBS [5], and the quarter-scale room model [6] used at NBS have also been included for comparison in some cases.

2. COMPARISON OF ASTM E 84 RATINGS WITH ROOM FIRE TESTS

In this section, the results of four separate projects in which E 84 ratings are compared with data from well-instrumented room fire tests are discussed. These include:

(1) a series of eight 9.5 x 10.5-foot room "corner fire" tests conducted at NBS by Fang [7], where the interior finish material being tested lined one rear corner;

(2) a series of 8 x 12-foot fully lined room fire tests at Underwriters Laboratories (UL) involving six materials, including four rigid foams [8];

(3) a cooperative project between CFR and the National Research Council of Canada (NRCC) in which eight materials, including five rigid foams, were evaluated in tunnel tests, room fire tests, corner tests, and various laboratory fire tests [9]; and,

(4) an extensive project at NBS on the fire safety of mobile homes where the interior finish materials were gypsum board, acoustic tile, and fire retardant-treated and untreated plywood [10-13].

These four series of tests are well enough documented (and familiar to the author) to serve as an adequate data base for assessing the strengths and weaknesses of the E 84 tunnel test as an indicator of room fire performance.

The tunnel test was designed for interior finish materials and, for a considerable period of time, was assumed to be quite adequate for that purpose. Because of the difference in exposure conditions between the tunnel and a room fire and also between one room fire and another, it could not be expected to rank the fire performance of materials exactly with respect to their performance in a particular room fire; but, in a gross way, it could be expected to distinguish between classes of fire performance. In particular, it should be able to identify any extraordinarily hazardous material. It was apparently able to do this fairly well for conventional materials. However, it was found to be deficient in the case of rigid plastic foams, some of which have a low FSC but still result in rapid flashover of a room. Such cases are documented in this section.

2.1 Room Corner Fire Tests at NBS

Two 1.2 x 2.4-m (4 x 8-ft) wall panels and one 1.2 x 2.4-m (4 x 8-ft) ceiling panel lined one rear corner of a 2.9 x 3.1-m (9.5 x 10.5-ft) room with a ceiling height of 2.4 m (7.9 ft) and a 0.90-m (35-in) wide by 2.0-m (80-in) high open doorway, as shown in Figure 1 [7]. The panels were attached to the structure with 19-mm (3/4-in) furring strips, leaving an air space. Two 1.2 x 2.4-m (4 x 8-ft) ACB panels were placed vertically between 1.2 and 2.4 m (4 and 8 ft) from the corner along each wall. The remainder of the room was finished with 16-mm (5/8-in) thick Type X gypsum wallboard protected with an asbestos fiber material. The ignition source was a 6.4-kg (14-lb) wood crib made up of 0.051 x 0.051 x 0.356-m (2 x 2 x 14-in) sticks of hemlock and located in the corner 0.051 m (2 in) away from each wall. The temperature reported here is the average of those recorded by thirty-six 0.51-mm (20-mil) chromel alumel thermocouples distributed over the upper half of the room.

Table 1 gives a comparison of the maximum gas temperature averaged over measurements in the upper half of the room with the results of the ASTM E 84, the ASTM E 162, and the NBS rate of heat release (RHR) calorimeter for five materials which were used for both the wall and the ceiling specimen panels. The materials are listed in descending order of the maximum temperature in the room. A good correlation is achieved with the E 84 and the RHR calorimeter in the sense that the ranking of the materials is the same as that for the maximum temperature.

In Table 2, the same comparison is made for eight materials where the materials were used for the two wall specimen panels only. A gypsum board ceiling was used for all of these tests. Since the contribution of the gypsum board was minimal, the temperature rises were smaller. Note that if only the materials listed in Table 1 are included, the correlation with the E 84 is equally good. However, it breaks down when fir and Lauan plywood are also included. If, instead, we use for the correlation the broad classes utilized by the building codes,

Class A	$0 \leq FSC \leq 25$
Class B	$26 \leq FSC \leq 75$
Class C	$76 \leq FSC \leq 200$
Class D	$201 \leq FSC \leq 500$
Class E	$500 \leq FSC$,

the correlation is again seen to be adequate for the intended purpose.

In another subset of these tests, the wall materials were varied while the ceiling panel was always acoustic tile. As seen in Table 3, there is very little correlation in this case, even for the broad classes of materials. Obviously the complex problem of a combustible ceiling and wall material does not lend itself to a simple evaluation criterion. It still retains one important safety feature, however. The Class B material with the FSC of 33 did, in fact, produce a minimal temperature rise.

The relative importance of the combustible ceiling compared to the wall materials and the variability of the tests probably were responsibile for the inconsistency with the earlier correlation.

2.2 Room Fire Tests at Underwriters Laboratories (UL)

Nine room fire tests were conducted at UL in a 2.4 x 3.7-m (8 x 12-ft) room with a 2.4-m (8-ft) ceiling and a 0.76-m (30-in) wide and 2.1-m (84-in) high doorway. The room was completely lined with the test material. Six of the tests used a 9.1-kg (20-lb) wood crib in the rear corner as an ignition source. The crib was made up of 0.051 x 0.051 x 0.38-m (2 x 2 x 15-in) white fir sticks. Although the temperatures also were measured 25 mm (1 in) below the center of the ceiling and 25 mm (1 in) from the ceiling and wall intersection--2.4 m (8 ft) from the ignition source, data were recorded on all six of these tests only at the location 25 mm (1 in) down from the top of the doorway. Both the maximum temperatures attained at the top of the doorway and the time to reach full involvement provide consistent bases for ranking and are listed in Table 4. These two indicators of fire performance are compared with the E 84 rating and, where they exist, with the E 162 and the NBS rate of heat release calorimeter data. The code listed in the table is that used in the UL report [8]. With these materials, a correlation does not follow from the data. The two rigid polyisocyanurate foams which had Class A ratings with FSC of 22 and 23, implying good fire safety performance, exhibited full involvement or flashover in times short compared to that of plywood having a FSC of 178. Furthermore, the time to reach full involvement depended on the transient fire development of the wood crib. It is noted that neither the E 162 or the heat release rate calorimeter would have provided a clue to the behavior of material A. Although the fire retardant-treated (F.R.) plywood was not reported as having full ceiling involvement, as would be indicated by flame out of the doorway, the amount of material destroyed and the temperature reached at the top of the doorway (715°C) were indicative of flashover conditions. Indeed, the edge of the doorway ignited in 385 seconds. This material had an FSC of 25. Thus, the failure of the FSC to denote materials that can lead to large fire development is not limited to low density plastic foams.

2.3 Room Fire Tests at NBS in Cooperation with NRCC

A series of room fire tests were then conducted at NBS with fiber glass, a 65 percent mineral and 35 percent cellulosic fiber insulating board, and five rigid cellular plastics covering a large range of FSC [9] in a 2.4 x 3.7-m (9.5 x 10-ft) room with a 0.74-m (29-in) wide and 1.9-m (76-in) high doorway. These materials fully lined the test room. The tests were carried out as a part of a cooperative research program with the National Research Council of Canada (NRCC), who obtained the FSC ratings on their ASTM E 84 tunnel. The ignition source was a natural gas diffusion burner located in one rear corner of the room and having a net heat release rate of 79 kW, which is equivalent to the burner in the ASTM E 84 tunnel.

At NRCC, the materials were subjected to (1) standard E 84 tests, (2) tunnel tests in which the material lined the rear wall and ceiling to simulate flame spread along the wall/ceiling intersection in the room fire, and (3) tunnel tests in which the material lined the ceiling only, but aluminum foil was placed on the floor to increase the radiation feedback. The FSC was calculated by three methods: the one specified in the standard at the time of these tests, the GWL method (which is used at the present time), and 5550 d_{MAX}/t' (which is now used in Canada for cellular plastics).

The additional tests performed on these materials included canopied corner tests and half-scale canopied corner tests at NRCC; and quarter-scale room fire tests, rate of heat release, and ease of ignition tests at NBS.

Table 5 provides a summary of the tests at NBS and the standard tunnel tests at NRCC. The results of the standard E 84 tunnel tests and the full- and reduced-scale corner tests eventually will be reported separately by NRCC. Data from room fire tests on plywood and PVC nitrile foam under similar conditions are included in this table for comparison. Materials C and B-2 exhibit the main problem of concern. While these materials had FSC values of approximately 30 (based on their short flame spread distances), putting them in the Class B category, they experienced flashover in substantially under 1 minute. This may have been expected from their observed rapid flame spread rate in the tunnel, which is not reflected in their FSC. The actual flashover times in these room fire tests are shorter than those for the foams in Table 4 because of the instantaneous constant fire exposure provided by the gas burner in the present tests compared to the development time required by the wood crib in the UL tests. It is seen that the new GWL method presently in use does not improve the correlation. However, using 5550 d_{MAX}/t' is a decided improvement but the very rapid flashover compared to plywood is still not predicted. When applying this method of calculation to material B-2 in three successive tunnel runs, a difficulty with this particular method becomes apparent. Although high flame spread rates were observed in the early part of the E 84 test for all three runs, the maximum distance was approached slowly in the first two--which resulted in uncharacteristically low values of 5550 d_{MAX}/t'. While observation of the performance of these materials in the tunnel indicates their hazardous nature, none of the present methods for the calculation of FSC provide an adequate measure of this potential hazard.

It is noted that the best correlation of the times-to-flashover in the room is obtained with the quarter-scale model room tests.

2.4 Full-Scale Mobile Home Fire Program at NBS

Ninety full-scale fire tests were conducted in the kitchen, corridor, bedroom, and living room areas of a single-wide mobile home, sponsored by the Department of Housing and Urban Development (HUD). Of interest here are the tests in the last three areas.

2.4.1 Corridor Tests

The corridor in this series of tests [10] measured 5.2 m (17 ft) in length, 0.76 m (2.5 ft) in width, and 2.1 m (6.9 ft) from floor to ceiling. A portion of the kitchen area was blocked off as seen in Figure 2, providing a small room which opened into the corridor. A 6.4-kg (14-lb) wood crib consisting of 0.051 x 0.051 x 0.36-m (2 x 2 x 14-in) sticks of hemlock was placed in one corner of the blocked-off area as seen in the figure. Nine tests were conducted using the four wall materials and three ceiling materials listed in Table 6. The maximum gas temperatures, developed 0.25 m (10 in) below the ceiling of the corridor at least 2.3 m (7.5 ft) from the wood crib, are compared with the E 84 and E 162 ratings in Table 7. The table is laid out to show the effect of varying the wall material while keeping the ceiling material constant. Within each group, the wall material is listed in order of decreasing FSC. It is seen that the ranking of the temperature rise is the same as that of the FSC of the wall material. On the other hand, when the wall material is maintained at an FSC of 194, the maximum temperature rise correlates with the FSC of the ceiling material. The correlation obtained with the E 162 test is not as good.

2.4.2 Living Room and Bedroom Tests

Figure 3 shows the layout of the mobile home for the bedroom and living room tests [11-13]. The exterior doors and the doors to bedrooms 2 and 3 and the bathroom were all closed during the test. The ignition source, which was either a 6.4-kg (14-lb) wood crib or a 16-kg (35-lb) upholstered chair, was located in a corner at the point labeled L for the living room fire tests. The 16-kg (35-lb) upholstered chair was also used as the ignition source in the bedroom fire tests. In that case, it was located in the far corner of bedroom number 1.

The test results are summarized in the Material Hazard Matrices in Figures 4 and 5. The shaded area represents that combination of wall and ceiling materials that lead to flashover in the particular room and for the particular ignition source specified. The time to flashover does not vary enough between materials because of their similar densities, to display any trend with the FSC. The maximum temperatures reached are not useful indicators for the fires that flash over, since extinguishment occurs soon after. However, in the case of the living room tests with the 6.4-kg (14-lb) wood crib and the gypsum board ceiling, flashover was not reached for any of the wall materials. Hence, the maximum temperature and heat flux to the floor can be compared with the E 84 rating in this case as shown in Table 8. It is noted that the maximum heat flux to the floor and the maximum temperature 0.25 m (10 in) down from the center of the ceiling correlates with both the old and the GWL method of calculation and with the rate of heat release in the NBS heat release rate calorimeter with an external radiant flux of 60 kW/m^2.

3. ANALYSIS

Perhaps the first interior measurements in the E 84 tunnel were made by Quintiere and Raines [14] in the Hardwood Plywood Manufacturer's Association (HPMA) tunnel. They measured the volumetric inflow of the air with a bank of pitot tubes and found it to vary during the course of the test. This has been corrected in the present standard by changing the mode of control. They also measured the temperature and thus the enthalpy flow with a bank of thermocouples at 4.6 and 7.3 m (15 and 24 ft) from the burner. These tests showed that approximately half of the energy from the gas burner is lost by radiation and convection to the bounding surfaces of the tunnel with an ACB specimen. The radiation losses should increase significantly with a smoke-producing specimen. The radiant heat flux was measured on the floor at 4.9 m (16 ft) using a radiometer with a sapphire window. The maximum radiant heat flux measured was 21 kW/m^2 during a standard test of a nylon carpet. This peak occurred at 230 seconds. The distance of the flame tip was reported to be 5.2 m (17 ft) at that time.

Measurements were made by Parker [15] of the heat flux, oxygen concentration, temperature, velocity, and pressure in a series of instrumented tunnel tests at the Underwriters Laboratories (UL) using [1] standard length specimens, (2) 0.91-m (3-ft) long specimens, and (3) a reference specimen consisting of ACB and an auxiliary controlled supply of methane. Five different flow rates of methane to the auxiliary burner provided constant and known heat inputs simulating the gaseous decomposition products from regular test specimens. Incident heat fluxes on an inert specimen as high as 63 kW/m^2 were measured within the flame impingement zone with a water-cooled total heat flux meter 0.61 m (2 ft) downstream from the burner.

The temperature of the lower exposed and upper unexposed surfaces of a 13-mm (1/2-in) thick Asbestos Mill Board (AMB) specimen is plotted as a function of distance after a 20-minute exposure in Figure 6. The maximum exposed surface temperature of 650°C occurs 0.61 m (2 ft) downstream from the burner. These temperatures were used along with the thermal conductivity of the AMB to estimate the heat transfer versus distance in the tunnel, as shown in Figure 7. The air temperature 13 mm (1 in) below the AMB surface is also recorded in Figure 6 and used to estimate the gas phase heat transfer. Figures 8 and 9 show the temperatures developed and the estimated heat fluxes for a full-length methane diffusion flame exposure of the specimen. The vertical gas temperature profiles for an ACB specimen are shown in Figure 10.

Figure 11 shows that the increase in the burner flame length was proportional to the increase in volume flow rate of the methane and thus to its increase in total heat release rate. An attempt was made to see whether there was a universal relationship between the heat release rate and the length of the flame, which applied to all materials. Specimens 0.91 m (3 ft) long of a number of materials and a full-length red oak deck were tested, and the flame extent was compared with that of methane in Figure 12. The best linear fit to the data points was $d = 0.61 + 0.049\,\dot{Q}$ where d is in meters and $\dot{Q}$ in kW. The heat release rates were determined using the oxygen consumption technique [16] by measuring the concentration of oxygen in the exhaust duct. It is not clear how much of the scatter of the data in Figure 12 is due to the absence of a well-defined relationship and how much due to the primitive nature of the oxygen consumption technique in 1974.

In another experiment, the exposed surface of a red oak specimen was instrumented with thermocouples so that the arrival of the 350°C isotherm, taken to be the location of the pyrolysis front, could be measured and compared with the position of the flame tip. It was found that flame extension led the pyrolysis zone by about 1.5 m (5 ft) over the whole test until the flame extended beyond the end of the tunnel.

A full-length fire retardant-treated rigid polyurethane foam with a density of 32 kg/m^3 (2 lbs/ft^3) was tested for 5 minutes. The flame spread for a maximum distance of 3.1 m (10 ft), which gave it an FSC of 28 using the calculation method which was in use at the time. This maximum distance was reached very rapidly in the test. After the test, the specimen was cut up into 0.3-m (1-ft) lengths and weighed. The residual weight was subtracted from the original weight, which was calculated from the average density of the specimen determined before the test. This difference was divided by the test duration to yield an average rate of weight loss versus distance as displayed in Figure 13. The peak value of the average burning rate occurred at about 0.46 m (1.5 ft) downstream of the burner with a magnitude of 3.6$g/m^2 \cdot s$ (2.65 $lb/ft^2 \cdot h$). However, this is an average value over the 5-minute interval, so the maximum was undoubtedly somewhat higher. Although the burning rate dropped sharply at the maximum reported flame spread distance, there was a significant amount of mass loss beyond it. This additional mass loss was apparently not sufficient to produce a combustible mixture and hence contributed only to the smoke production. The decomposed depth was also measured and plotted in Figure 14 for each section. It can be seen that a 5-minute exposure was not sufficient to consume the whole depth of the 51-mm (2-in) specimen. Since the maximum distance was reached within a few seconds, the burnout of the specimen was not a reason for the flame failing to spread further.

Since oxygen depletion was often quoted as the reason for the flame to stop spreading, oxygen concentration profiles were taken at various distances and times for ACB and regular specimen tests. The drop in oxygen concentration on the floor of the tunnel was very small, as seen in Figure 15, for the above foam. This corresponds to the oxygen concentration in the free stream away from the wall or under the ceiling layer in a room fire. Hence oxygen depletion was not the reason for the difference between the performance of this material in a room and in the tunnel. It was also noted that varying the volumetric air flow rate into the tunnel from 4 to 13 m^3/s had little impact on the maximum flame spread distance, further evidence that oxygen depletion is not the reason that the flame stopped at a particular distance.

The flame spread distances for the low FSC materials were nearly the same for the 7.3-m (24-ft) and 0.91-m (3-ft) specimens even though the leading edge of the flame was adjacent to an ACB surface in the latter case, indicating that the local conditions near the flame front were not controlling factors in the extent of the spread. It is clear that the flame spread distance recorded in the tunnel is the extension of the burner flame rather than a surface flame spread.

A hypothesis is advanced here in an attempt to explain why the flame stops in the tunnel for some materials, and yet those same materials may provide the conditions necessary for the rapid flashover of a room when they are mounted on the wall or ceiling. Based on the experiments in the tunnel with different flow rates of methane and the 0.91-m (3-ft) specimens discussed above, the flame area (A_f) is assumed to be proportional to the total rate of heat production ($\dot{Q}$), so that

$$A_f = f\dot{Q} \tag{1}$$

or, since the spread is one dimensional,

$$X_f = f\dot{Q}' \tag{2}$$

where f is the constant of proportionality equal to 0.022 m^2/kW, X_f is the flame distance, and $\dot{Q}'$ is the total heat release rate per unit width of the specimen. The value of 0.022 m^2/kW for f was found by multiplying the slope of the line in Figure 12 by the width of the tunnel. Since the materials of concern here have essentially the same rate of heat release per unit mass of oxygen consumed (13.1 MJ/kg), the constancy of f depends on the constancy of the oxygen supply rate per unit area normal to the surface, assuming that all of the oxygen entering the flame zone is immediately consumed and that the reaction goes completely to water and carbon dioxide. For a smooth surface, the turbulent boundary layer thickness grows as $X^{4/5}$. Since the amount of oxygen ingested by the flame is proportional to the boundary layer thickness, the total rate of heat release is proportional to $X_f^{4/5}$ so that X_f is proportional to $(\dot{Q}')^{5/4}$. The changes in the properties of the gases in the boundary layer due to combustion are neglected and the effects of externally induced turbulence by the floor, walls, and turbulence bricks are ignored in this calculation. Since it is difficult at the present time to make an adequate theoretical model which will properly account for all of the relevant factors, the empirical relationship displayed in equation (1) will be used in the following analysis.

Consider the one-dimensional flame spread problem in general for the underside of a surface assuming the linear relationship expressed by equation (1). First, assume that the fuel comes only from the burning specimen. Then

$$A_f = f\dot{Q} = f\bar{q}A_p, \tag{3}$$

where A_p is the pyrolyzing area of the material and $\bar{q}$ is the average heat release rate per unit area of the pyrolysis zone.

Since the flame must cover the pyrolyzing area to maintain the flow of combustible volatiles, $A_f \geq A_p$. Hence, a material for which $f\bar{q}$ is less than unity will not support a flame in the absence of external fuel sources and can be labeled "self extinguishing". If $f\bar{q} > 1$, then $A_f - A_p$ is the flame extension which heats up a new area to the pyrolysis temperature in a time τ_p. If the net heat flux from the flame to the surface, $\dot{q}_f''$, is assumed to be constant and the material can be considered to be thermally thick up to the time that its front surface reaches the pyrolysis temperature T_p, then τ_p, which is equivalent to the time to ignition can be determined from classical heat conduction theory [17]:

$$T_p - T_s = \frac{2}{\sqrt{\pi}} \frac{\dot{q}_f'' \sqrt{\tau_p}}{\sqrt{K\rho C}} , \tag{4}$$

where T_s is the surface temperature prior to the arrival of the flame, K is the thermal conductivity of the material, ρ is the density of the material, and C is its heat capacity.

The pyrolyzing area will continue to increase at a rate given by

$$\dot{V}_p = \frac{dA_p}{dt} \cong \frac{A_f - A_p}{\tau_p} = \frac{(f\bar{q}-1)A_p}{\tau_p} \tag{5}$$

It must be recognized that, in general, $\bar{q}$ depends on A_p, since the heat release rate per unit area varies over the pyrolyzing area.

The material can be considered to be self-propagating if $f\bar{q} > 1$ and self-extinguishing if $f\bar{q} < 1$, since $\frac{dA_p}{dt}$ is negative. In the latter case A_p will shrink to a point and the flame will extinguish. If a material is self-propagating in the tunnel, it will be self-propagating in a room fire because of the higher heat release rates due to higher incident fluxes. Flashover will be inevitable if the room is lined with this material since it has been observed that flashover has occured or is imminent by the time that flames cover the upper part of the room and extend to the doorway.

We are more concerned with those materials whose flames stop within the tunnel, because it is some of these materials which were determined to be safe by the E 84 but proved to be hazardous in a room fire. We are trying to establish the reason here. If the burner in the tunnel produces a flame area (A_o) and the material has a pyrolyzing area (A_p) with an average rate of heat release ($\bar{q}$), then the total flame area will be

$$A_f = A_o + f\bar{q}A_p, \tag{6}$$

where $f\bar{q}A_p$ is the additional flame area provided by the burning of the volatile pyrolysis products from the specimen. It should be noted that the pyrolyzing area A_p includes the area A_o covered by the burner flame. Using equations (4) and (6), the rate of increase of the pyrolyzing area is given by

$$\frac{dA_p}{dt} = \frac{A_f - A_p}{\tau_p} = (A_o + (f\bar{q}-1)A_p)/\tau_p, \tag{7}$$

where τ_p is determined from equation (4) to be

$$\tau_p = \pi K\rho C \, (T_p - T_s)^2/4\dot{q}_f''^2. \tag{8}$$

If $f\bar{q} > 1$, the flame will continue to propagate indefinitely. If $f\bar{q} < 1$ the pyrolyzing area will continue to grow until

$$A_p = A_o/(1-f\bar{q}). \tag{9}$$

Then $\frac{dA_p}{dt} = 0$ and the flame ceases to propagate.

Also, by equation (7), $A_p = A_f$ when $\frac{dA_p}{dt} = 0$ so that

$$A_f = A_o/(1-f\bar{q}). \tag{10}$$

Assuming that $\bar{q}$ is a constant for a particular material, the integration of equation (7) yields

$$A_p = \left(\frac{A_o}{1-f\bar{q}}\right) (1 - \exp(-(1-f\bar{q})t/\tau_p)). \tag{11}$$

Combining equations (6) and (11),

$$A_f = \left(\frac{A_o}{1-f\bar{q}}\right) (1 - f\bar{q}\exp(-(1-f\bar{q})t/\tau_p)). \tag{12}$$

Since $A_f = WX_f$, where W is the width of the tunnel, the length of the flame is given by

$$X_f = \left(\frac{X_o}{1-f\bar{q}}\right) (1 - f\bar{q}\exp(-(1-f\bar{q})t/\tau_p)) \tag{13}$$

When $t = 0$, $X_f = X_o = 1.37$ m (4.5 ft), the length of the burner flame at the beginning of the test. If $f\bar{q}$ is less than unity, the flame stops at a distance $X_f = X_o/(1-f\bar{q})$. If $f\bar{q}$ is close to unity, X_f may exceed the length of the tunnel. The flame spread distance in the tunnel is given by

$$d = X_f - X_o = \frac{X_o f\bar{q}}{1-f\bar{q}} (1 - \exp(-(1-f\bar{q})t/\tau_p)). \tag{14}$$

When $f\bar{q} < 1$, there is a maximum flame spread distance found by setting $t = \infty$,

$$d_{MAX} = \frac{f\bar{q}X_o}{1-f\bar{q}} . \tag{15}$$

For the flame to stop within the tunnel, d_{MAX} must be less than 5.95 m (19.5 ft) and therefore $f\bar{q}$ must be less than 0.81.

The flame spread classification (FSC) prior to 1977 was given by

$$FSC = 16.7\ d_{MAX},\ \text{if } X_f \le 5.5 \text{ m (18 ft), and} \tag{16a}$$

$$FSC = 50 + 4.63\ d_{MAX},\ \text{if } X_f > 5.5 \text{ m (18 ft)} \tag{16b}$$

Hence,

$$FSC = 16.7\ f\bar{q}X_o/(1-f\bar{q}),\ \text{if } X_f \le 5.5 \text{ m (18 ft), and} \tag{17a}$$

$$FSC = 50 + 4.63\ f\bar{q}X_o/(1-f\bar{q}),\ \text{if } X_f > 5.5 \text{ m (18 ft)} \tag{17b}$$

The quantities d_{MAX} and X_o are expressed in meters.

For those materials for which the flame stopped in the tunnel, there should be a correlation between the heat release rate and the FSC. It is difficult to determine the proper external radiation level that should be used in the heat release rate calorimeter to represent the average exposure condition on the specimen in the tunnel. Furthermore, it is not clear whether to take the maximum heat release rate or that averaged over some time interval which would need to be determined. Nevertheless, the peak heat release rates measured at a 30 kW/m^2 external radiant flux level in the NBS heat release rate calorimeter are recorded in Table 9 for the materials used in the U.L. study [8]. The heat release rates and measured flame spread classifications are taken from Table 3 of reference [15]. Material Q, also listed in that table, was not included because of the extreme variability in observed fire performance from specimen to specimen. The actual value of $\bar{q}$ can be estimated for material B which had a burning rate in the tunnel of 2.0×10^{-3} $kg/m^2 \cdot s$ (1.47 $lb/ft^2 \cdot h$) averaged over the 10-ft flame length for the first five minutes of the test as seen in figure 13. The effective heat of combustion of a similar FR polyurethane foam (GM-31 in the Products Research Committee Materials bank [18]) was reported to be 11.5 MJ/kg, giving an approximate value of 23 kW/m^2 for $\bar{q}$, which also happens to be the maximum heat release rate of material B listed in Table 9. The calculated flame spread distance from equation (15) was 1.37 m (4.5 ft), compared to the measured flame spread distance of 1.68 m (5.5 ft).

The calculated values of $f\bar{q}$, d_{MAX} (equation 15), and the FSC for those materials with $f\bar{q} < 1$ (equation 17a) are also listed in Table 9 along with the measured distances and the FSC values determined from them. If $f\bar{q} < 1$ or $\bar{q} < 45$ kW/m^2, the flames were confined to the tunnel. If $f\bar{q} > 1$, the flames passed out the end of the tunnel.

The imprecision of $\bar{q}$ makes a quantitative comparison impossible but qualitatively the flame spread distance and FSC show a high dependence on the heat release rate for those materials whose flames remain in the tunnel as expected from the equations. The flame spread classifications determined in the E 84 test are roughly ranked in the same order as the heat release rates. It is natural to suppose that if the heat release rates in a room fire are higher because of the greater expected heat transfer rates, then the extent of the flame spread could be much larger. In particular, if $f\bar{q}$ becomes greater than unity, the flames would become self-propagating and a fully developed fire would result. Furthermore, if $K\rho C$ were small, τ_p would be small and the flame coverage would be very rapid as seen from equation (12), which could be written

$$A_f = \frac{A_o}{f\bar{q} - 1} (f\bar{q}\exp((f\bar{q}-1)t/\tau_p)-1). \tag{18}$$

The effect of external radiation on the flame spread distance was demonstrated at the National Research Council of Canada (NRCC) by putting aluminum foil on the floor of the tunnel to reflect more of the radiation back onto the specimen. The average flame spread distance of an FR polyurethane foam (Material C in Table 5) was increased from 1.83 m (6 ft) to 2.44 m (8 ft) when the foil was placed on the floor. This result was based on an average of 3 specimens in each case.

If the flame passes out the end of the tunnel in time t*, the flame spread classification prior to 1977 was given by

$$FSC = 33000/t^*, \quad \text{if } t^* \leq 330 \text{ s, and} \tag{19a}$$

$$FSC = 50 + 16500/t^* \text{ if } t^* > 330 \text{ s,} \tag{19b}$$

where t* is in seconds.

Putting X_f = 7.32 m (24 ft) and X_o = 1.37 m (4.5 ft) into equation (13) and solving for t yields

$$t^* = \frac{\tau_p}{f\bar{q}-1} \ln\left(\frac{1 + 5.33\ (f\bar{q} - 1)}{f\bar{q}}\right) \tag{20}$$

Values of τ_p determined from the time of the first reported flame travel in the tunnel are listed in Table 9 along with the calculated FSC for materials with $f\bar{q} > 1$ using equations (19a) and (20). The calculated values are high, presumably due to the expected increase in τ_p and the decrease in q with distance in the tunnel. These quantities are dependent on the incident heat fluxes which decrease with distance in the tunnel as illustrated in figure 9 for a specimen fully covered with flame. The variation in τ_p and $\bar{q}$ with distance are not accounted for in these simple derivations. Nevertheless, there is a rough ordering of the observed FSC with that calculated from equations 19a and 20. In particular, there is an order of magnitude change in the FSC between materials H and O, which have the same heat release rate but an order of magnitude difference in τ_p. The $K\rho C$ is 1.85×10^{-1} and 1.35×10^{-3} $kW^2 \cdot s/deg^2 \cdot m^4$ for materials H and O, respectively. For those materials which pass flame out the end of the tunnel, the FSC was more dependent on τ_p than $\bar{q}$. For those materials for which the flame stops in the tunnel, the FSC was independent of τ_p. For instance, material B has an order of magnitude lower τ_p than material J but one half as great a heat release rate and one half of the FSC.

At the present time, the flame spread index (FSI) is determined by the GWL method which is based on the area under the flame spread distance versus time curve, A_T.

$$FSI = 0.0281\ A_T, \text{ if } A_T \leq 1780 \text{ m·s, and} \tag{21a}$$

$$FSI = \frac{89700}{3560 - A_T}, \text{ if } A_T > 1780 \text{ m·s.} \tag{21b}$$

The integral of equation (14) up to time t* plus the product of the remaining time of the test and the maximum flame spread distance yields.

$$A_T = \left(\frac{X_o f\bar{q}}{1-f\bar{q}}\right)\left[t^* - \tau_p\left(\frac{(1-\exp(-(1-f\bar{q})t^*/\tau_p))}{(1-f\bar{q})}\right)\right] + 5.95\ (t_T - t^*) \tag{22}$$

where $X_o = 1.37$ m.

For those cellular plastics with low flame spread classifications τ_p and $f\bar{q}$ are small so that equation (22) can be approximated by

$$A_T = \left(\frac{X_o\, f\bar{q}}{1-f\bar{q}}\right)\left(t_T - \frac{\tau_p}{(1-f\bar{q})}\right) \tag{23}$$

The maximum flame spread rate, $\dot{d}$, found by differentiating equation (14) and setting t=0, is given by

$$\dot{d} = X_o f\bar{q}/\tau_p = \frac{4X_o\ f\bar{q}\ \dot{q}_f''^2}{\pi K\rho C(T_p-T_s)^2}\ . \tag{24}$$

While the maximum flame spread rate is inversely proportional to $K\rho C$ and thus very high for the low density foams, the thermal inertia only appears as a small correction, through τ_p, in the GWL formula presently used in the E 84 standard. This new calculation, like its predecessor, does not adequately reflect the rapid fire build up potential of these materials.

This situation was remedied to some extent by a formula proposed by D'Souza and McGuire [19] and adopted in Canada for foams. It is given by

$$FSI = 5550\ d_{MAX}/t' \tag{25}$$

where t' is the time in seconds to reach the maximum distance, d_{MAX} in meters. This index measures a flame spread rate for those materials whose flames stop within the tunnel. However, as seen by equation (14), the maximum distance is approached exponentially but never reached. The asymptotic distance can easily be determined but assigning a time is quite subjective. In practice, $\bar{q}$ may decrease slightly creating a maximum but it is still slowly approached so that flame spread rates determined from equation (21) may be appreciably less than the maximum flame spread rate indicated by equation (24). Nevertheless, equation (25) provides a much better indication of the rapid fire buildup potential of the low density foams than the GWL or the previous formula.

The foregoing equations were developed on the basis of a semi-infinite solid which continued burning at essentially the same rate during the course of the test or at least until the flame had essentially reached a maximum distance or passed out the end of the tunnel. This approximation is probably adequate for most materials. However, thin combustible facings, such as the paper on gypsum board or on fiber glass, only burn for a short time. In the case of a material with high thermal inertia, such as gypsum board, the paper is burned up before its flame extension can heat the surface above it to the pyrolysis temperature. In that case the maximum flame extension lasts only for a brief period of time and is simply given by

$$d_{MAX} = f\bar{q}X_o \qquad (26)$$

According to the GWL calculation method, the distance at a particular time is equal to the maximum flame spread distance up to that time (i.e. any flame recession is not taken into account), and

$$A_T = f\bar{q}\, X_o\, (t_T - \tau_p), \qquad (27)$$

where τ_p is the time to pyrolysis or ignition of the surface and t_T is the time of the test. This is equivalent to the calculational procedure used prior to 1977 in which the FSC was equal to 16.6 d_{MAX}, ignoring any recession.

In the case of paper faced fiber glass, the low thermal inertia allows the material above the flame extention to be heated quickly to its pyrolysis temperature and the flame spreads rapidly to the end of the tunnel resulting in the highest reported flame spread classification in Table 9 (FSC = 2540).

The above simplified treatment of flame spread in the tunnel provides a qualitative explanation of why materials with low heat release rates provide flames which extend some distance down the tunnel and then remain relatively stationary for the remainder of the test thus receiving a low flame spread classification. The strong dependence of the flame spread distance on the average heat release rate of the material, which in turn depends on the heat transfer to the surface, suggests that materials whose flames stop within the tunnel may propagate flames much farther in a room fire where the external radiation levels are expected to be much higher. In fact, materials which are "self extinguishing" in the tunnel ($f\bar{q} < 1$) may become self-propagating ($f\bar{q} > 1$) in a room fire.

According to Table 4, materials S and A had flame spread classifications of 22 and 23 which corresponded to average flame spread distances in the tunnel of 4.3 and 4.5 feet, yet led to full involvement of an 8 x 12-ft room in 80 and 100 seconds. A large part of this time was due to the fire buildup time of the wood crib. Material C in table 5 which had an FSC of 30, or a flame spread distance in the tunnel of 6 feet, flashed over a 10 x 10-ft room in 18 seconds when the exposure flame was provided by a gas burner. The high flame spread rates for these foam plastics were also observed in the tunnel but were not reflected in their flame spread classifications. The size of the exposure flame (A_o) provided by the burner or by a piece of furnishing in an actual room fire is also an important factor in the extent of the flame spread as seen by equation (15).

4. SUMMARY

A comparison was presented between the room fire performance in four different full-scale fire test series and the flame spread classification obtained by the ASTM E 84 tunnel test for a wide range of materials. The fire performance in the room was measured in terms of maximum upper air temperature reached and the time to flashover. Although a reasonably good correlation in terms of rank order was obtained for the conventional interior finish materials, this correlation broke down when low density materials were included in the comparison. While the E 84 tunnel serves a useful function for the control of conventional building materials by the building codes, it should not be used to evaluate innovative materials for which no documented fire experience exists.

A flame spread hypothesis was presented which can account for the stopping of the flame in the tunnel for low heat release rate materials and for the difference in the performance of a material in the E 84 tunnel test and a room fire test. A self-extinguishing material can be defined as one whose rate of fuel production when exposed only to its own flame is insufficient to maintain that flame. If such a the total rate of heat production by the specimen. The total flame area can be expressed by

$$A_f = \frac{A_o}{1-f\bar{q}}$$

where A_o is the area of the exposing flame, $\bar{q}$ is the specimen's average heat release rate per unit area over it's total flame exposed area, and f is the ratio of the flame area to the total rate of heat release by the flame. The value of f is assumed to be a constant, equal to 0.022 m^2/kW for this hypothesis, although it may be material and orientation dependent. If $f\bar{q} \geq 1$ the flame will continue to propagate indefinitely. The flame area is a strong function of $\bar{q}$, which depends on the incident heat flux (which has been observed to be considerably higher on the average in the room than in the E 84 tunnel). Thus, a material with a low flame spread rating by the E 84 test may spread flame rapidly over the entire upper surface of a room and produce flashover in a few seconds, as was the case for material C in Table 5.

5. ACKNOWLEDGMENT

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6. REFERENCES

[1] ANSI/ASTM E 84-80, 1980 Annual Book of Standards, Part 18, American Society for Testing and Materials, pp. 795-808.

[2] ANSI/ASTM E 603-77, 1980 Annual Book of Standards, Part 18, American Society for Testing and Materials, pp. 1158-1180.

[3] ANSI/ASTM E 162-79, 1980 Annual Book of Standards, Part 18, American Society for Testing and Materials, pp. 902-913.

[4] Parker, W. J. and Long, M. E., "Development of a Heat Release Rate Calorimeter at NBS," Ignition, Heat Release, and Noncombustibility of Materials, ASTM STP 502, American Society for Testing and Materials (1972), pp. 135-151.

[5] Lawson, J. R. and Parker, W. J., "Development of an Ease of Ignition Test Using a Flame Exposure," NBSIR 82-2503 (June 1982).

[6] Parker, W. J. and Lee, B. T., "A Small-Scale Enclosure for Characterizing the Fire Buildup Potential of a Room," NBSIR 75-710 (June 1975).

[7] Fang, J. B., "Fire Buildup in a Room and the Role of Interior Finish Materials," TN 879, National Bureau of Standards (1975).

[8] Castino, G. T., Beyreis, J. R., and Metes, W. S., "Flammability Studies of Cellular Plastics and Other Building Materials Used for Interior Finishes," Underwriters Laboratories, Inc., Northbrook, Illinois (1975).

[9] Parker, W. J., "Comparison of Selected Room Fire Tests with ASTM E 84 and Other Laboratory Fire Tests", NBSIR (to be published).

[10] Budnick, E. K., "Fire Spread Along a Mobile Home Corridor," Nat. Bur. Stand. (U.S.), NBSIR 76-1021 (July 1976).

[11] Budnick, E. K and Klein, D. P., "Mobile Home Fire Studies: Summary and Recommendations," NBSIR 79-1720 (March 1979).

[12] Budnick, E. K., "Mobile Home Living Room Fire Studies: The Role of Interior Finish," Nat. Bur. Stand. (U.S.), NBSIR 78-1530 (September 1978).

[13] Budnick, E. K., Klein, D. P., and O'Laughlin, R. J., "Mobile Home Bedroom Fire Studies: The Role of Interior Finish," Nat. Bur. Stand. (U.S.), NBSIR 78-1531 (September 1978).

[14] Quintiere, J. G. and Raines, J. W., "Thermal and Flow Characteristics of the ASTM E 84 Tunnel Test Method," Nat. Bur. Stand. (U.S.), NBSIR 75-705 (September 1975).

[15] Parker, W. J., "An Investigation of the Fire Environment in the ASTM E 84 Tunnel Test, NBS Technical Note 945 (August 1978).

[16] Parker, W.J., "Calculations of the Heat Release Rate by Oxygen Consumption for Various Applications," NBSIR 81-2427-1 (March 1982).

[17] Carslaw, H.S. and Jaeger, J.C., Conduction of Heat in Solids, 2nd Edition, Oxford University Press, 1959, p. 75.

[18] Lyons, John W., Chairman, "Fire Research on Cellular Plastics:The Final Report of the Products Research Committee", Vol. 2, "Materials Bank Compendium of Fire Property Data", Nat. Bur. Stand. (U.S.), February 1980.

[19] D'Souza, M.V. and McGuire, J.H., "ASTM E 84 and the Flammability of Foamed Thermosetting Plastics", Fire Technology, Vol. 13, No. 2, May 1977.

Table 1. Comparison of Maximum Room Temperature with Laboratory Fire Tests for Materials Located on Both Walls and Ceiling in NBS Room Corner Tests

Wall Material	Maximum Upper Gas Temperature (°C)	E 84 FSC	E 162 FSI	Maximum Heat Release Rate at 60 kW/m^2 (kW/m^2)
Melamine Hardboard	803	226	117	520
Particleboard	719	153	118	210
Acoustic Tile	537	101	60	120
Gypsum Board	129	24	8	74*
Asbestos Cement Board	107	0	0	0

*Short duration pulse due to burning of the paper

Table 2. Comparison of Maximum Room Temperature with Laboratory Fire Tests for Materials Mounted on Wall Only in NBS Room Corner Tests

Wall Material*	Maximum Upper Gas Temperature (°C)	E 84 FSC	Class	E 162 FSI	Maximum Heat Release Rate at 60 kW/m^2 (kW/m^2)
Melamine Hardboard**	662	226	D	117	520
Fir Plywood	571	103	C	135	160
Particleboard**	549	153	C	118	210
Lauan Plywood	439	167	C	141	170
Acoustic Tile**	390	101	C	60	120
Coated Acoustic Tile	299	70	B	6	60
Vinyl/Gypsum Board	147	33	B	23	60
Gypsum Board**	129	24	A	8	74***

*Gypsum board ceiling
**Materials also included in Table 1
***Short duration heat pulse due to burning of paper

Table 3. Comparison of Maximum Room Temperature with Laboratory Fire Tests for Various Wall Materials with an Acoustic Tile Ceiling in NBS Room Corner Tests

Wall Material	Maximum Upper Gas Temperature (°C)	E 84 FSC	Class	E 162 FSI	Maximum Heat Release Rate at 60 kW/m^2 (kW/m^2)
Particleboard*	705	153	C	118	210
Melamine Hardboard*	701	226	D	117	520
Fir Plywood	683	103	C	135	160
Acoustic Tile*	537	101	C	60	120
Lauan Plywood	508	167	C	141	170
Vinyl-Coated Gypsum Board	153	33	B	23	60

*Material included in Table 1

Table 4. Room Fire Tests at Underwriters Laboratories

Material	Code	Time to Full Involvement (s)	Maximum Temperature (°C)	E 84 FSC	Class	E 162 FSI	Maximum Heat Release Rate at 30 kW/m^2 (kW/m^2)
Unfaced Polyisocyanurate Foam 2.3 PCF	S*	80	935	22	A	331-419	21
Unfaced Polyisocyanurate Foam 1.9 PCF	A	100	927	23	A	3	8.1
Untreated Plywood 1/4 in. thick	H	260	866	178	C	--	120
F.R. Treated Plywood 1/2 in. thick	G	∞	715	23	A	--	< 3
Aluminum Foil-faced Polyisocyanurate Foam 2.3 PCF	R	∞	343	27	B	3	< 3
Polystyrene Board Stock 1.8 PCF	N	∞	204	3	A	--	--

*Same as R with foil removed

Table 5. Comparison of Times to Flashover in Room Fire Tests with Laboratory Fire Tests in the NBS/NRCC Cooperative Program

Material Description	Code	Time to Flashover in Room (s)	Time to Flashover in 1/4-scale Model (s)	Std	GWL	FSC 5550	d_{MAX}/t'	Maximum Heat Release Rate at 20 kW/m^2 (kW/m^2)	Time to Ignition (s)
Rigid Polyurethane Foam	A	13	18	500	440	500		140	1.8
Rigid Polyurethane Foam	B	14	19	250	215	564		140	1.7
Rigid Polyurethane Foam	C	18	32	30	33	124		47	2.8
Rigid PVC Nitrile Foam	B-2	42	97	31 31 28	33 34 31	62 102 300		100	9
Plywood	H	156	185	178	N/A	178		120	52
Polyisocyanurate Foam	D	368	∞**	20	22	113		13	2.7
Foil-faced Polyisocyanurate Foam	E	∞	∞	20	18	28		7	16
65% Mineral 35% Cellulose Fiber Board	F	∞	∞	15	15	25		28	∞
Fiber Glass	G	∞	∞	15	15	30		< 3	∞

**When the gas flow to the burner was increased by 50%, flashover occurred in 53 s.

Table 6. Materials Used in the Mobile Home Fire Tests

Description	Material Designated Symbol	Thickness (mm)	Thickness (in)	E 84 FSC	E 162 FSI
Printed, paper-overlaid, embossed, grooved gypsum board	W-1	7.92	5/16	24	27
Prefinished, paper-overlaid, grooved lauan plywood	W-2	6.35	1/4	109	103
Prefinished, printed, grooved lauan plywood; intumescent coating	W-3	4.00	5/32	55	2
Prefinished, printed, grooved lauan plywood	W-4	4.00	5/32	194	149
Prefinished lauan plywood	W-5	4.00	5/32	202	159
Prefinished lauan plywood	W-9	6.00	1/4	151	198
Prefinished lauan plywood; intumescent coating	W-10	4.00	5/32	54	9
Prefinished lauan plywood; fire retardant vinyl coating	W-11	4.00	5/32	62	56
Vinyl latex prefinished (12 x 12 in) mineral fiberboard	C-1	10.30	1/2	19	2
Printed, grooved fiber-board; back surface exposed	C-2	10.30	1/2	81	152
Prefinished fiberboard tile (12 x 12 in)	C-3	10.30	1/2	122	80

Table 7. Comparison of Maximum Temperatures in Mobile Home Corridor Fire Tests with ASTM E 84 Flame Spread Ratings

Material		Maximum Temperature in Corridor (°C)	E 84 FSC		E 162 FSI	
Ceiling	Wall		Ceiling	Wall	Ceiling	Wall
C-1	W-4	694	19	194	2	149
C-1	W-2	505	19	109	2	103
C-1	W-3	259	19	55	2	2
C-1	W-1	225	19	24	2	27
C-2	W-4	763	81	194	152	149
C-2	W-3	320	81	55	152	2
C-3	W-4	804	122	194	80	149
C-3	W-4/1*	750	122	--	80	--
C-3	W-1	261	122	24	80	27

*W-4 was backed with W-1

Table 8. Comparison of Maximum Temperature and Maximum Heat Flux to the Floor with the ASTM E 84 Classifications in the Mobile Home Living Room Fire Tests

Material Code	Maximum Upper Air Temperature (°C) 250 mm Below Ceiling	25 mm Below Ceiling	Maximum Heat Flux on the Floor (kW/m^2)	E 84 FSC Std	GWL	Class	E 162 FSI	Maximum Heat Release Rate at 60 kW/m^2 (kW/m^2)
W-5	381	426	60	202	182	C	159	170
W-9	360	450	54	151	160	C	198	160
W-11	313	422	38	62	56	B	66	140
W-10	217	349	18	54	41	B	9	120
W-1	116	150	7	24	24	A	27	50

Table 9. Comparison of calculated and measured flame spread, classifications for materials used in the series of fire tests run at Underwriters Laboratories, Inc.

Material	Code	Measured τ_p (s)	Measured $\bar{q}^*$ (kW/m^2)	Calculated $f\bar{q}$	Calculated d_{MAX}^{**} (ft)	Calculated FSC	Measured FSC	Measured d_{MAX}^{**} (ft)
Gypsum Wallboard	W	39	< 3	< 0.07	< 0.3	< 2	13	2.5
F.R. Particle Board	T	71	< 3	< 0.07	< 0.3	< 2	18	3.5
F.R. Wood Fiber Board	I	61	< 3	< 0.07	< 0.3	< 2	18	3.5
Unfaced Fiber Glass	E	43	< 3	< 0.07	< 0.3	< 2	18	3.5
FR Plywood	G	39	< 3	< 0.07	< 0.3	< 2	23	4.5
FR Polyisocyanurate	A	5	8	0.18	1.0	5	22	4.3
Foil Faced FR Polyisocyanurate	R	20	< 3	< 0.07	< 0.3	< 2	26	5.1
FR Polyisocyanurate	S	4	23	0.51	4.5	23	28	5.5
FR Polyurethane	C	5	23	0.51	4.5	23	28	5.5
FR Polyurethane	B	4	23	0.51	4.5	23	28	5.5
Wood Fiberboard	J	31	40	0.88	33	168	54	11
Red Oak	AE	49	94	2.1	∞	625	100	∞
Particle Board	U	47	110	2.4	∞	780	156	∞
Lauan Plywood	H	39	120	2.6	∞	1040	178	∞
F.R. Polyurethane	O	4	120	2.6	∞	10100	1738	∞
Paper Faced Fiber Glass	F	9	130	2.9	∞	5180	2540	∞
Glass Reinforced Polyester	M	-	140	3.1	∞	-	367	∞
F.R. Polyurethane	D	-	190	4.2	∞	-	925	∞

* Since $\bar{q}$ could not be measured directly, the values of the maximum heat release rates at an external heat flux of 30 kW/m^2 in the NBS heat release rate calorimeter were used instead.

** Feet are used instead of meters since feet is the unit of measurement in the test.

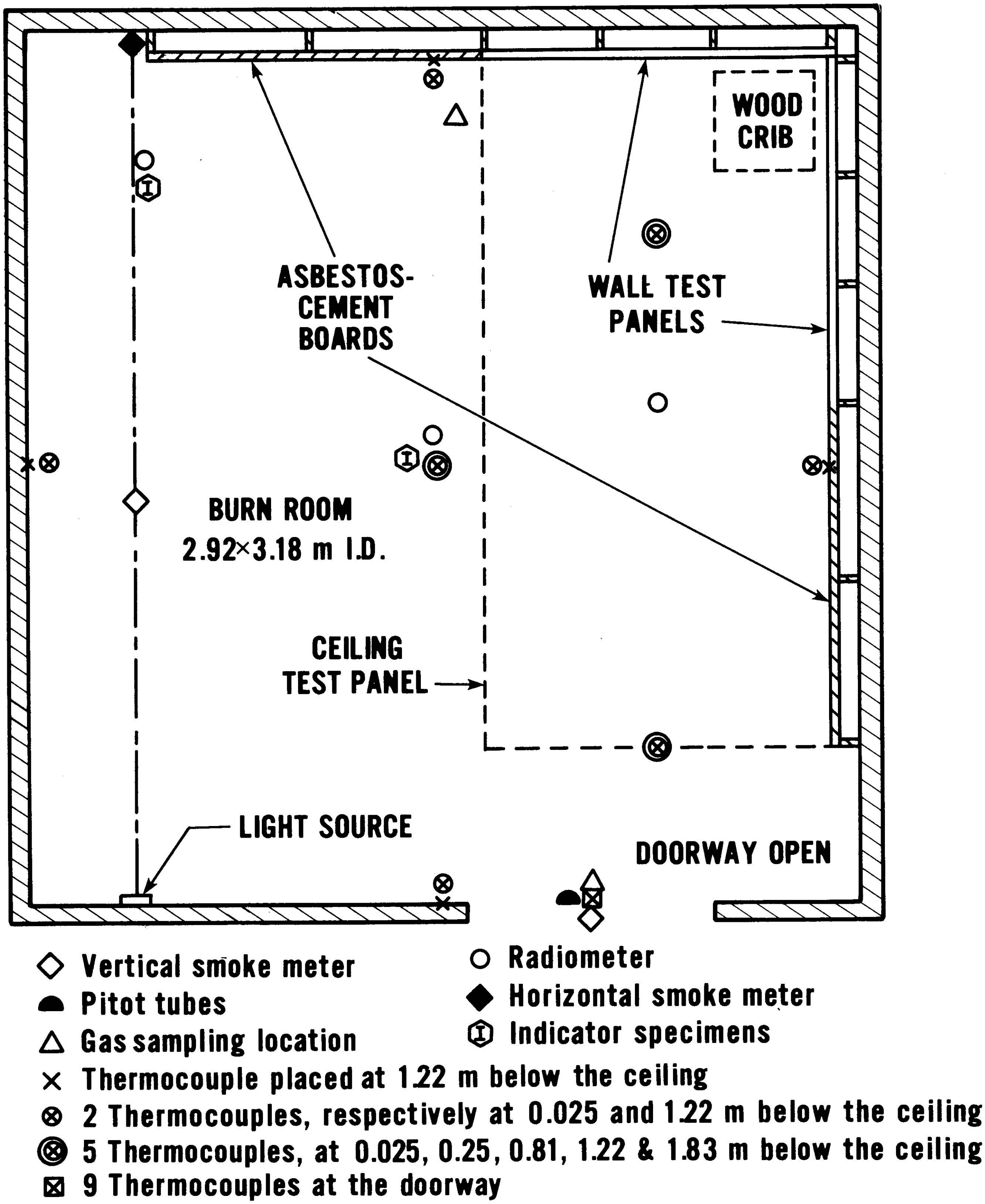

Figure 1. Plan view of the burn room showing locations of test panels and wood crib, and arrangement of instrumentation.

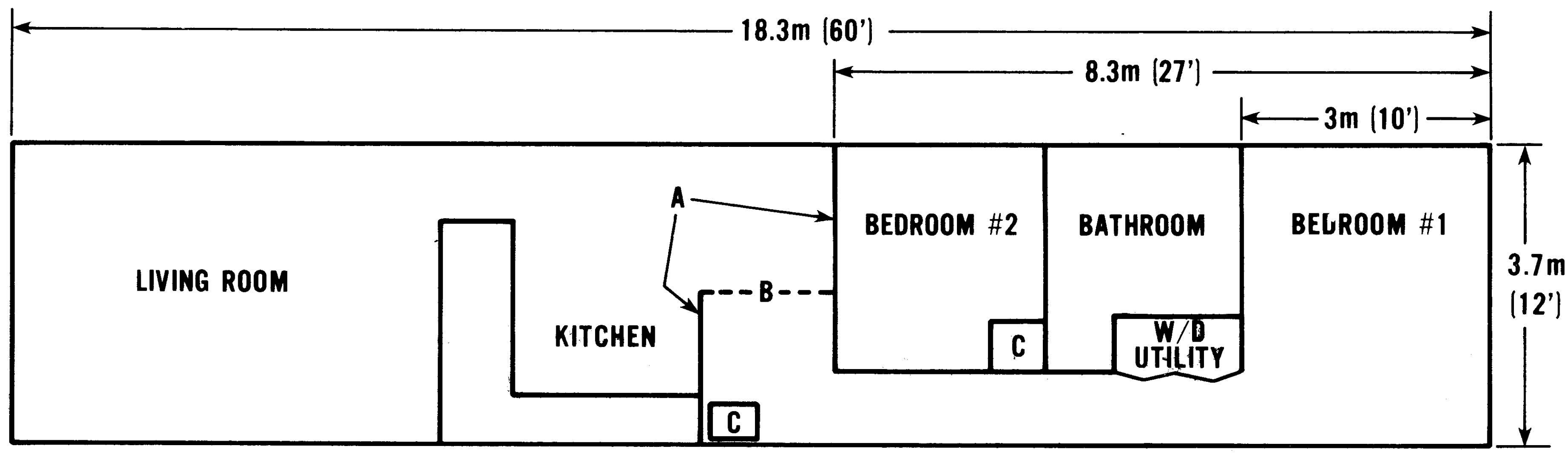

Figure 2: Floor plan of mobile home used in corridor tests

A - Partitions covered with asbestos-cement board

B - Draft curtain extended down 20 cm from ceiling

C - Ignition Source

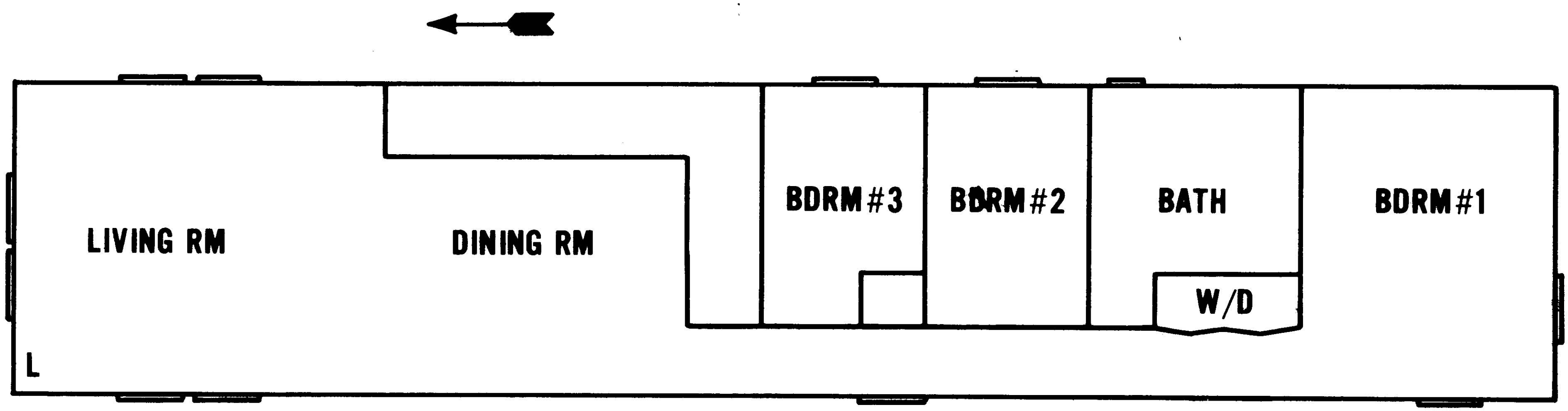

Figure 3. Plan view of mobile home used in living room tests

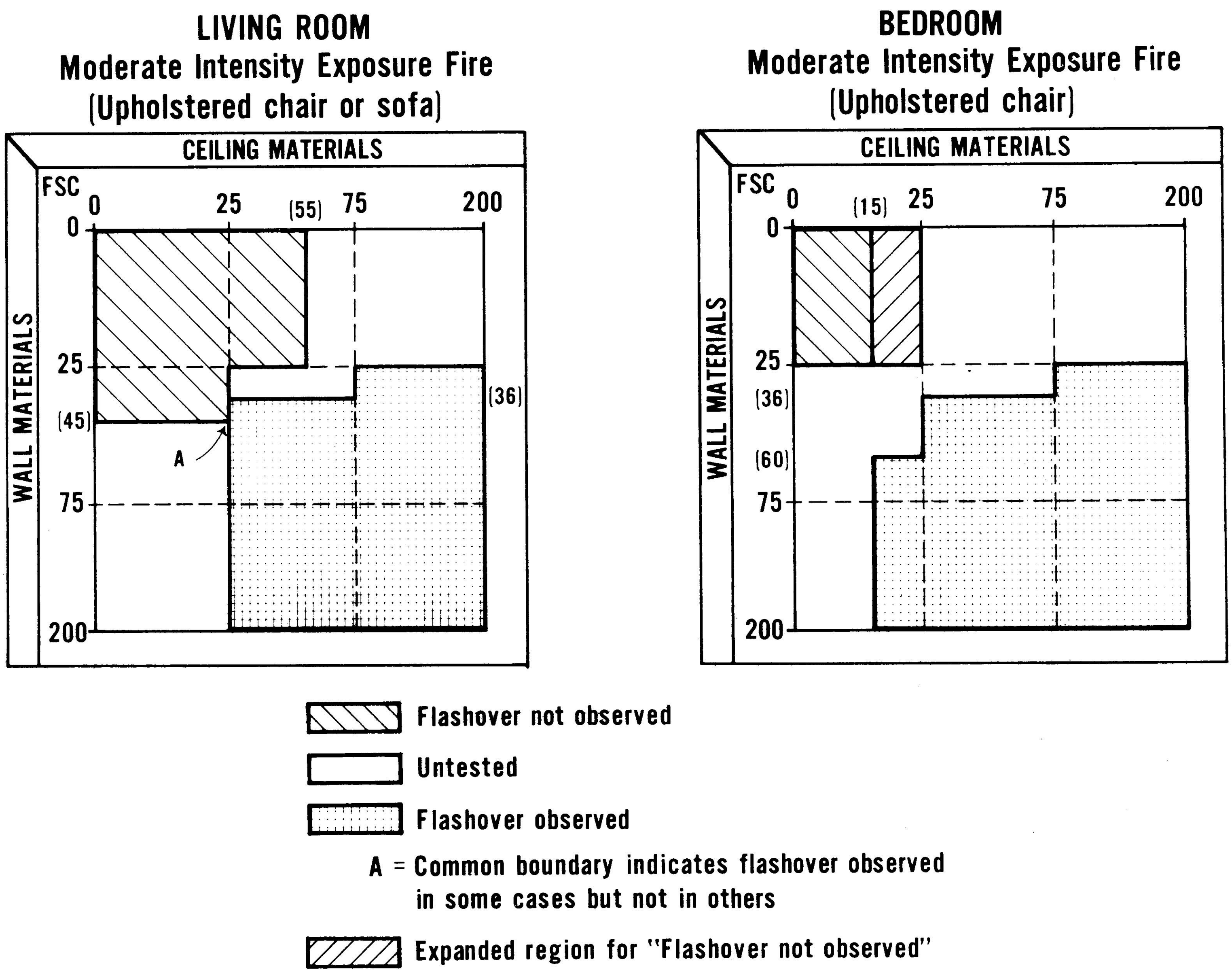

Figure 4. Material hazard matrices for moderate intensity exposure fires in the living room and bedroom (based on ASTM E 84 FSC).

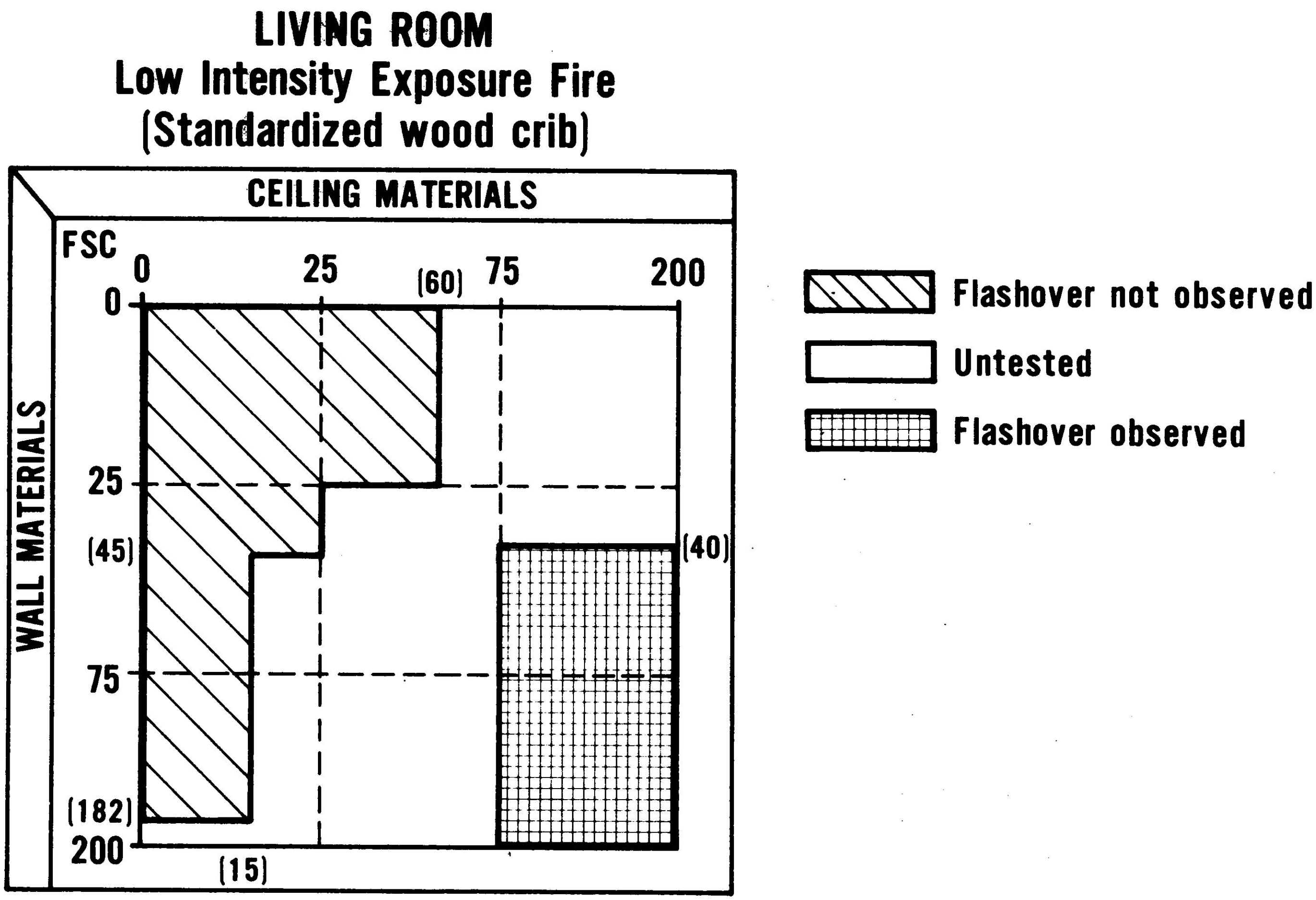

Figure 5. Material hazard matrix for low intensity exposure fire in living room (based on ASTM E 84 FSC)

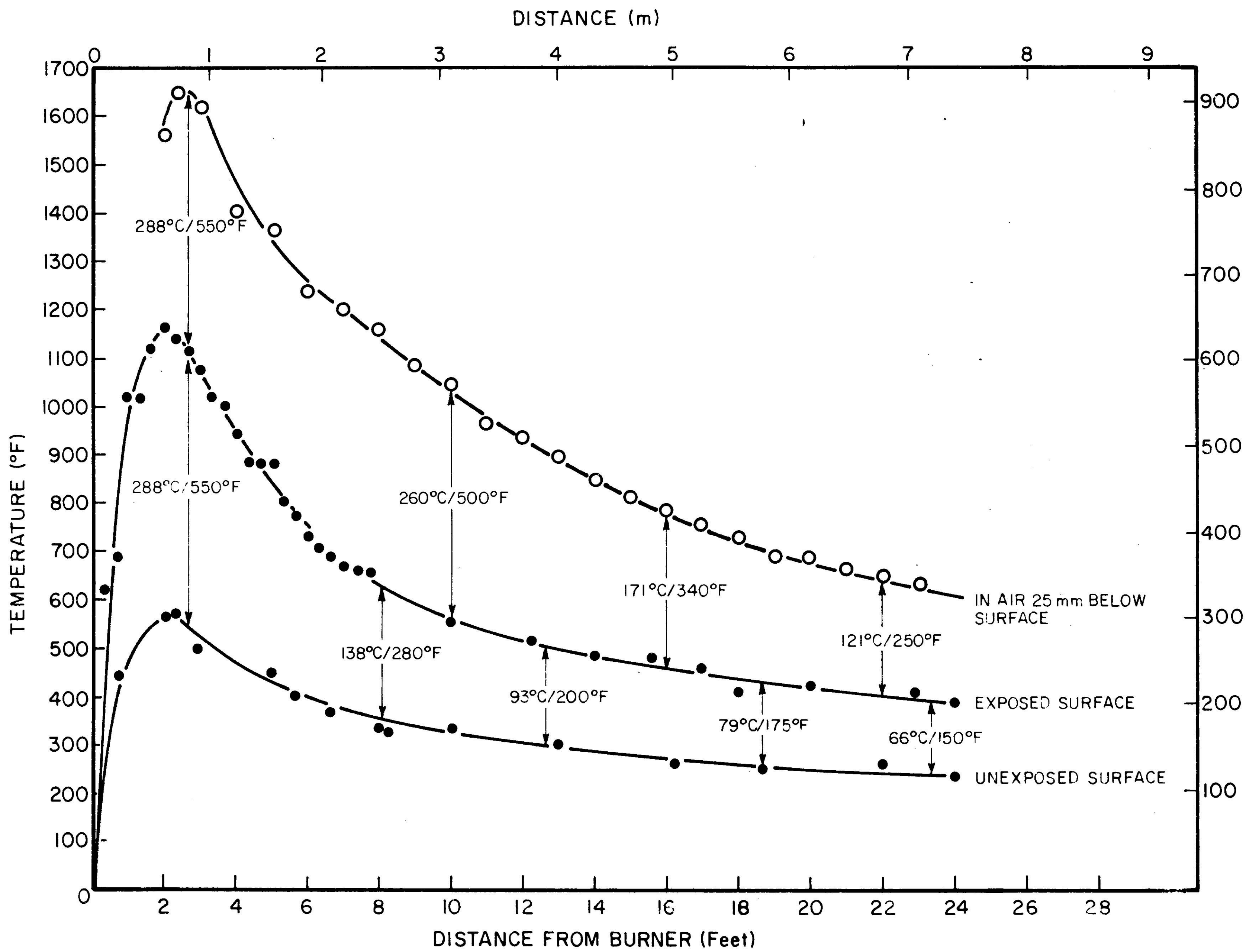

Figure 6. Temperature distribution along exposed and unexposed surfaces of AMB specimen

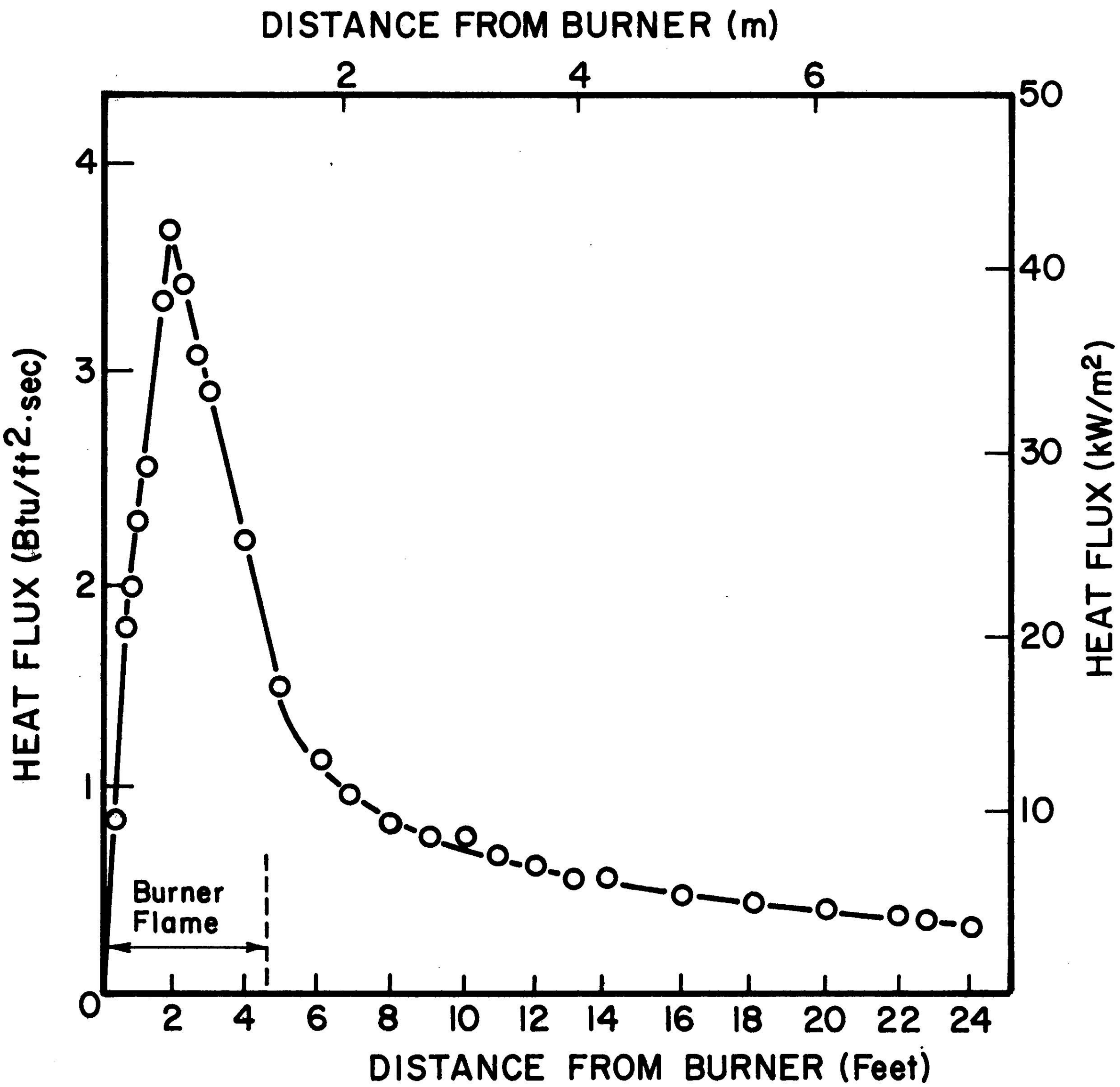

Figure 7. Incident heat flux distribution along an AMB specimen.

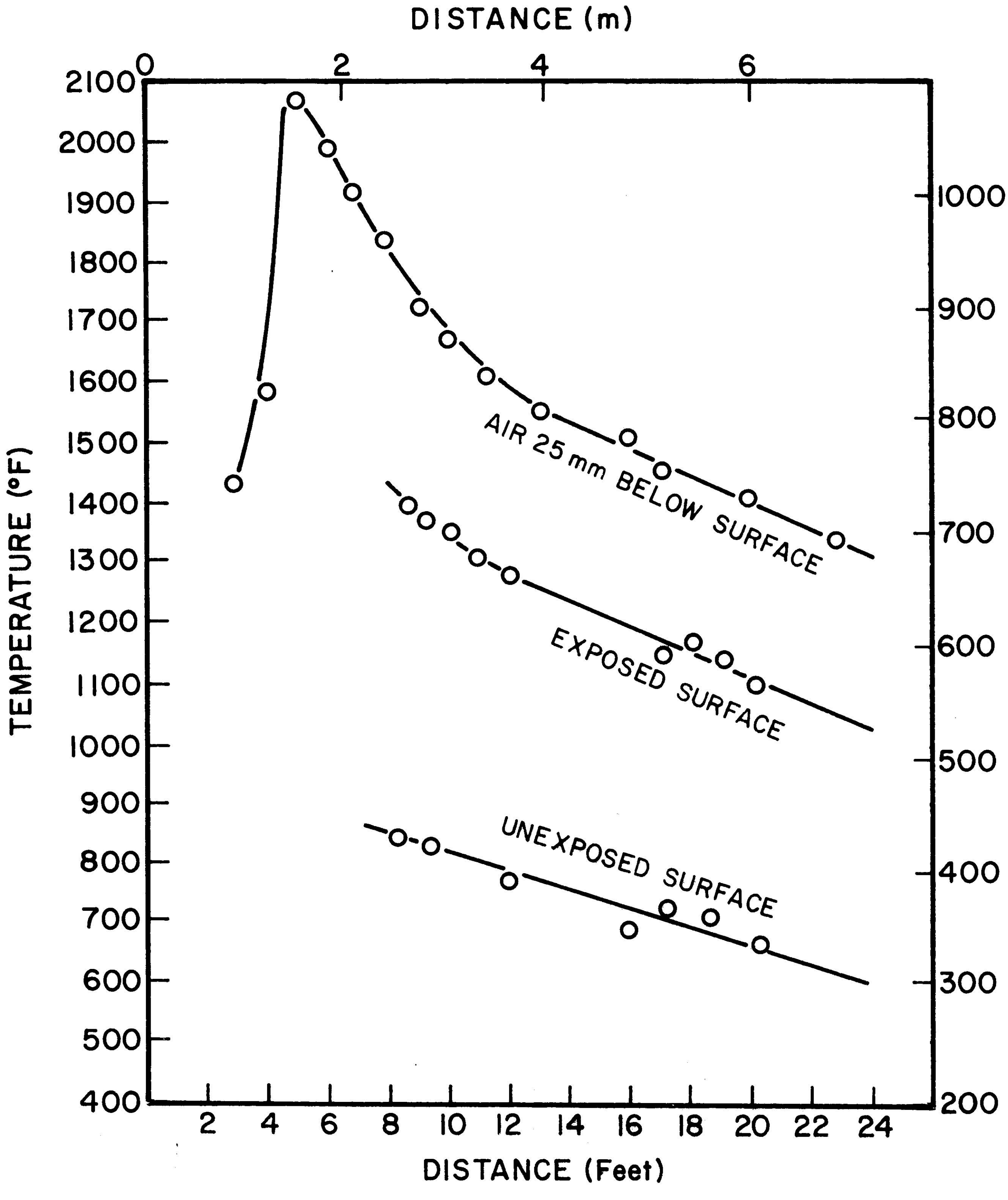

Figure 8. Temperatures distribution along exposed and unexposed surfaces of AMB specimen fully bathed in flame

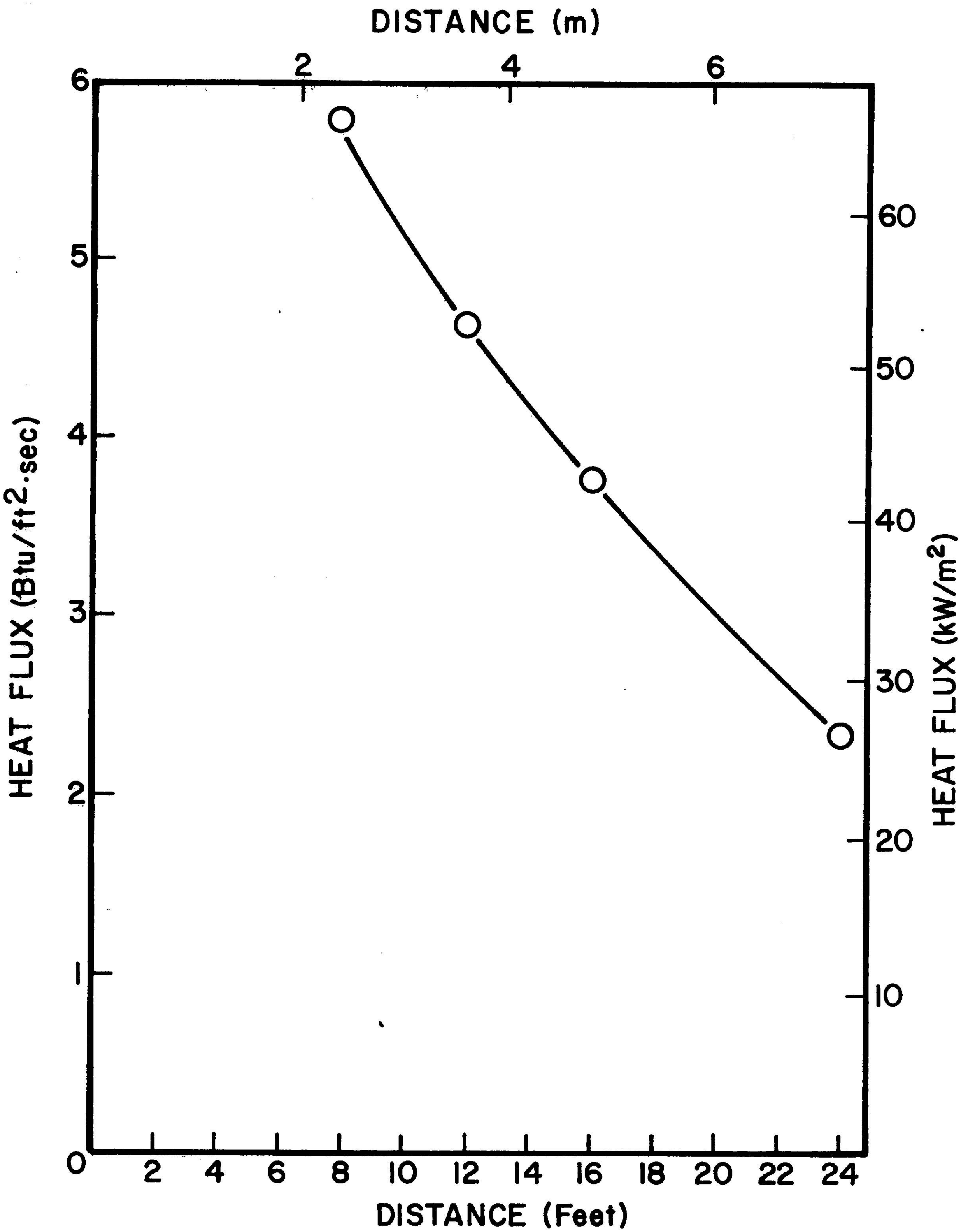

Figure 9. Incident heat flux distribution along an AMB specimen fully covered with flame.

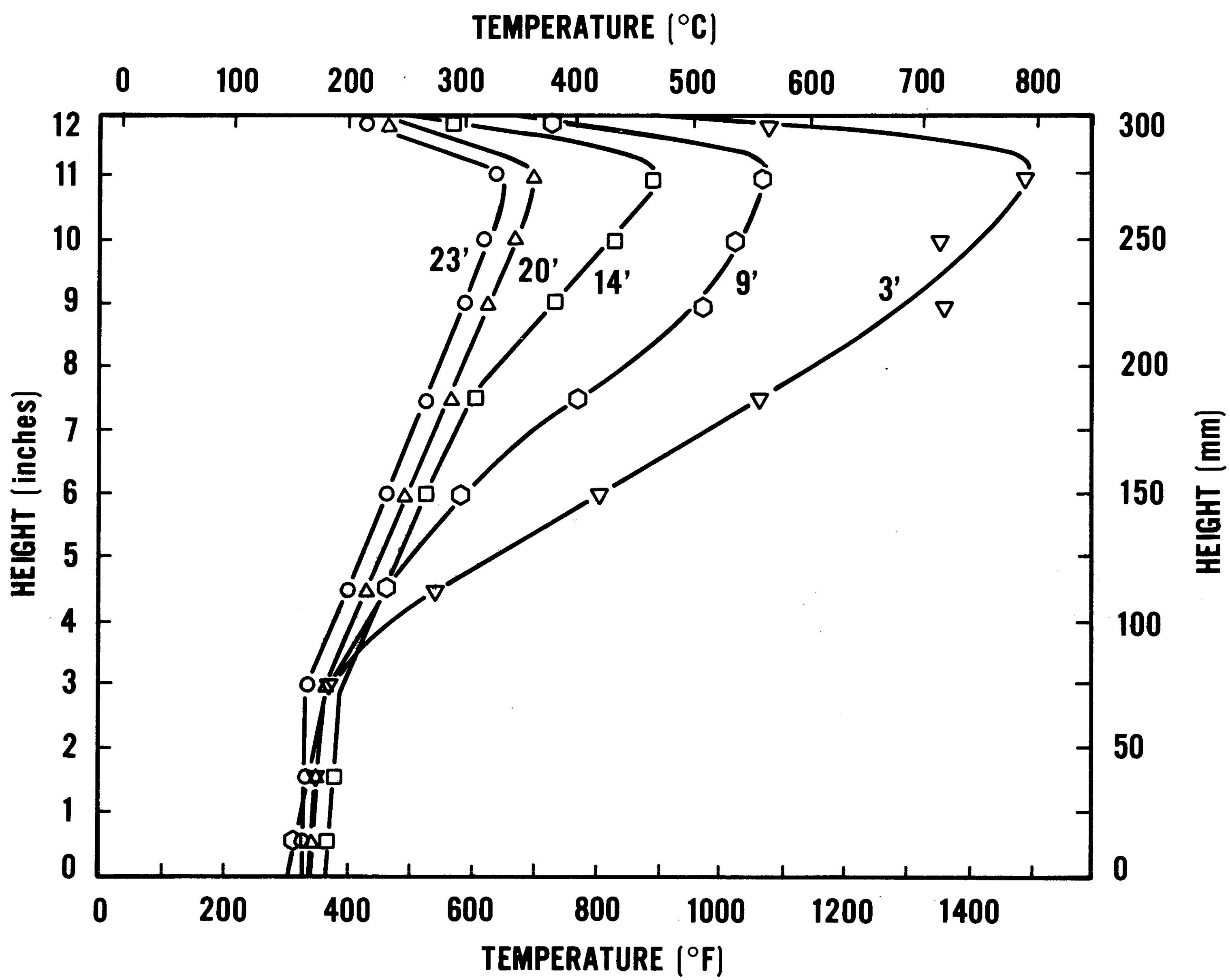

Figure 10. Centerline air temperature profiles at various distances in the tunnel for an ACB specimen at 10 minutes.

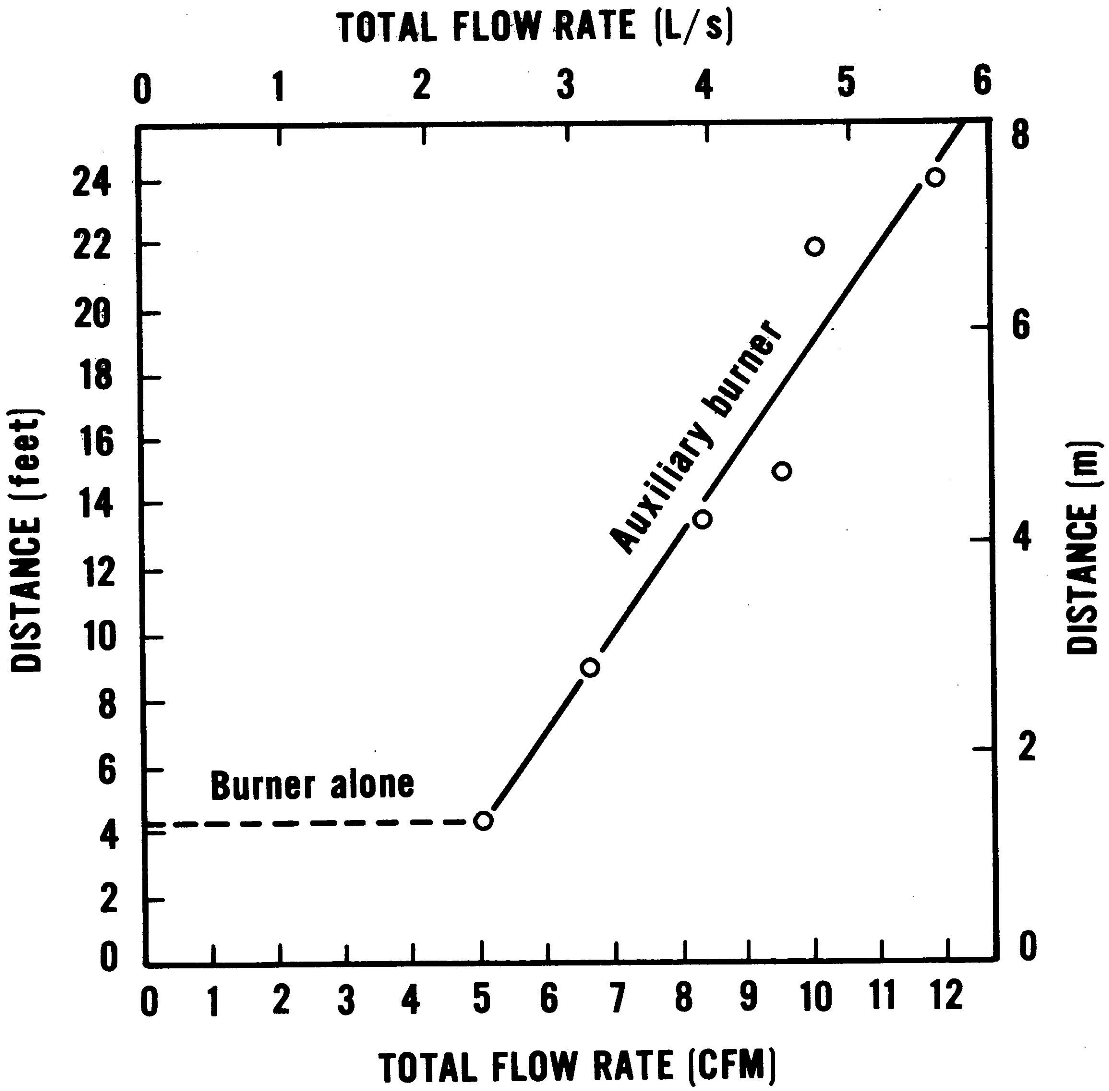

Figure 11. Flame spread distance versus total methane flow rate in auxiliary burner.

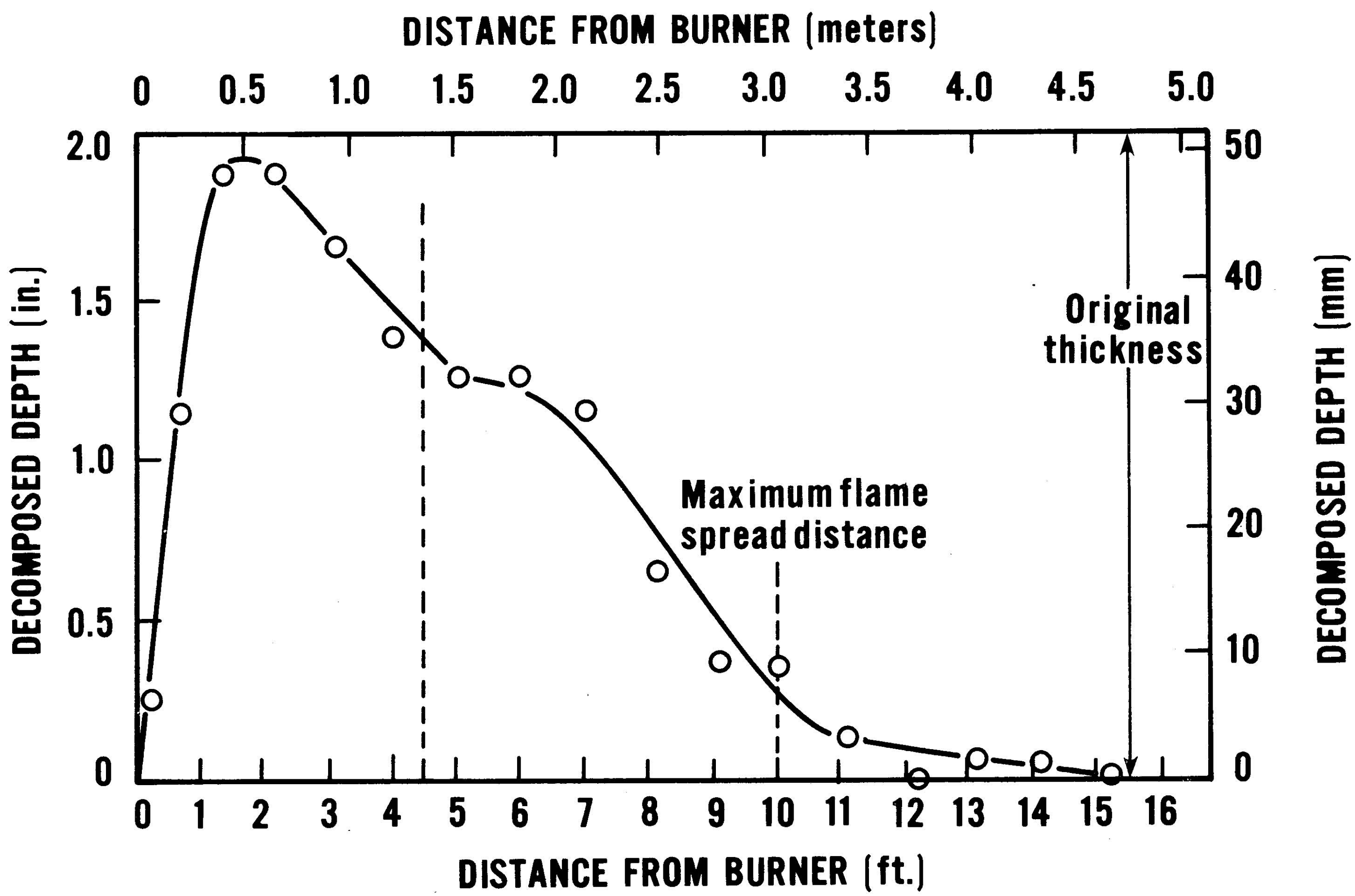

Figure 14. Decomposed depth versus distance for type B specimen.

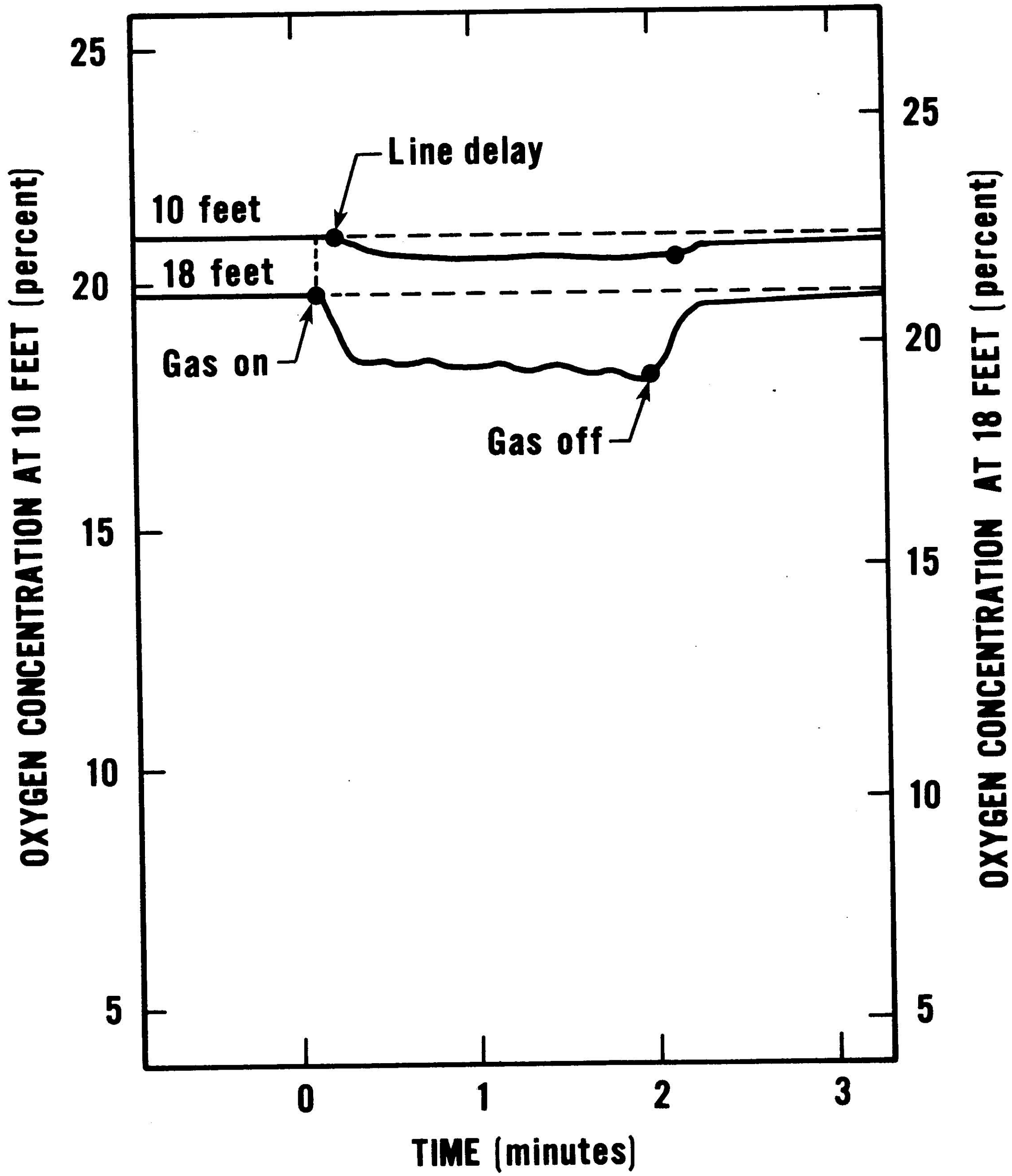

Figure 15. Chart record of oxygen concentration on the floor of the tunnel at 10 and 18 feet for a type B specimen (1 foot = 0.305 meters)

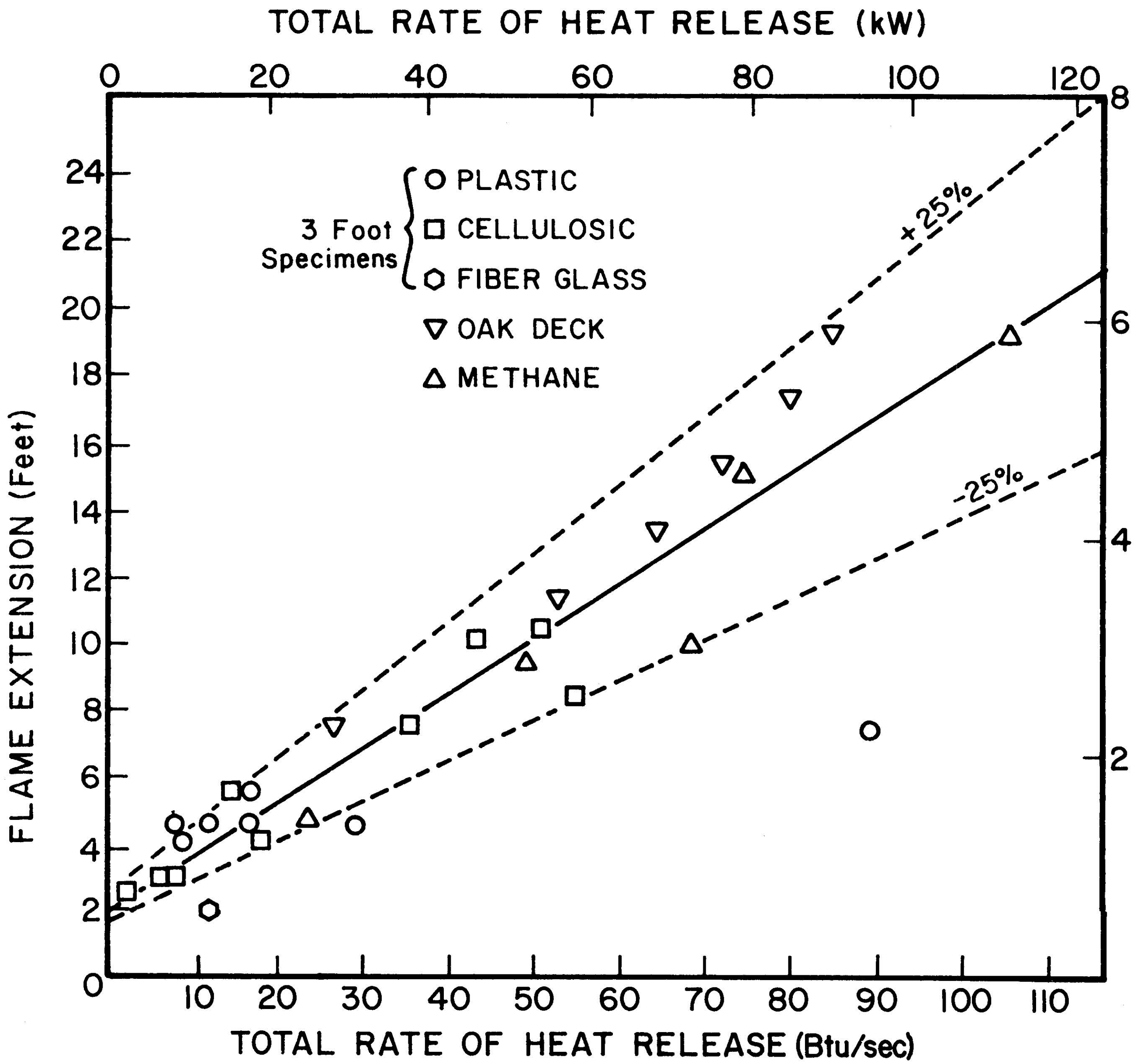

Figure 12. Flame distance versus total heat release rate in the tunnel

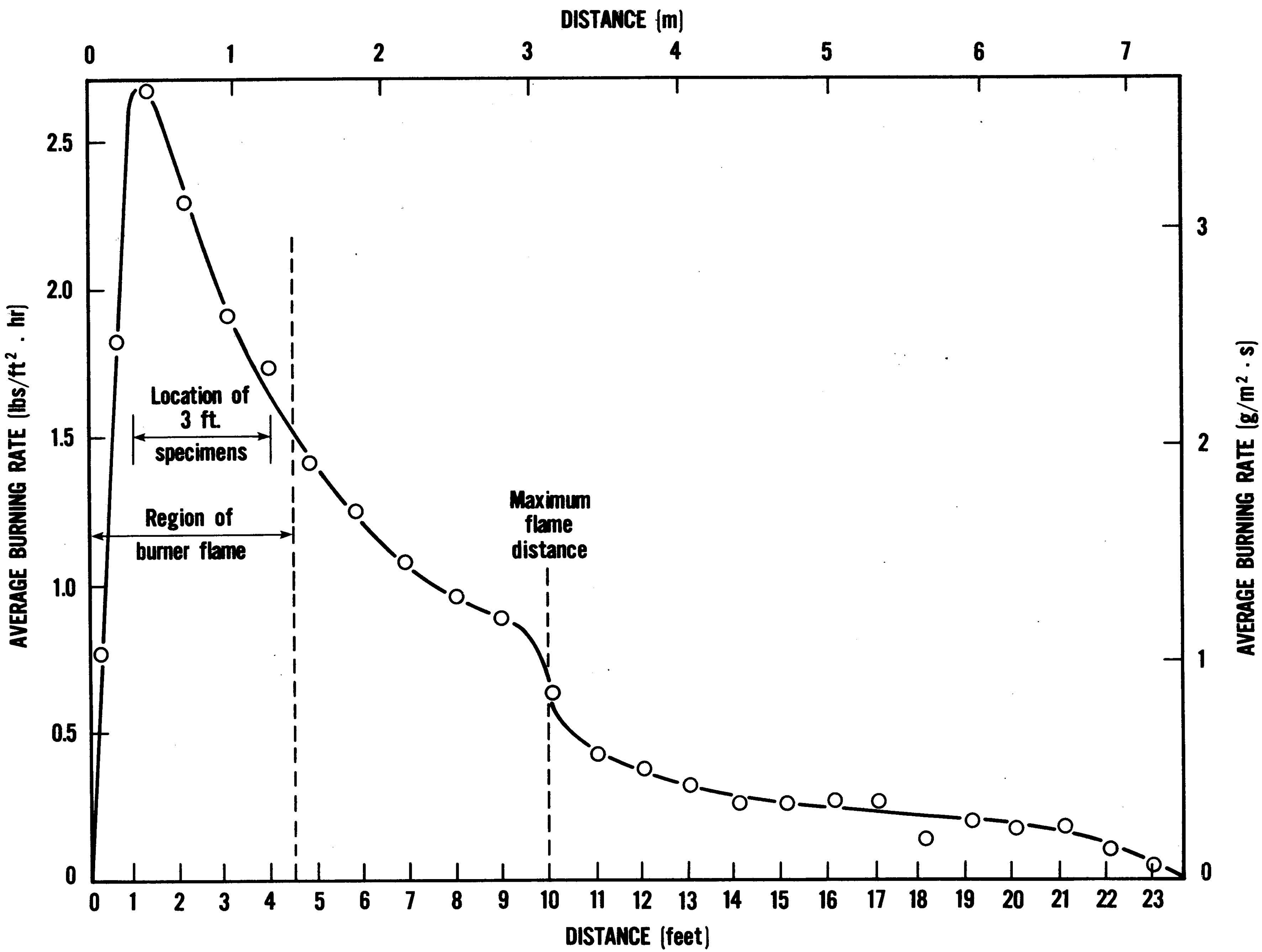

Figure 13. Average burning rate distribution along a type B specimen

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A comparison is presented between the room fire performance in four different full scale fire test series and the flame spread classification obtained by the ASTM E 84 tunnel test for a wide range of materials. A good correlation is obtained only for conventional interior finish materials. A flame spread hypothesis is presented to account for the stopping of the flame in the tunnel and the difference in the fire performance of materials in the tunnel test and in the room fire test.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

ASTM E 84; fire tests; flame spread; heat release; room fires

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